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Operation and control of concentrated solar power system integrated with thermal energy storage system

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สิทธิพร วงศ์สิโรจน์กุล : การดำเนินการและการควบคุมระบบพลังงานสุริยะเข้มข้นร่วมกับระบบกักเก็บพลังงานความร้อน (Operation and control of concentrated solar power system integrated with thermal energy storage system) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร. สุรเทพ เขียวหอม, 72 หน้า.

งานวิจัยนี้มีจุดประสงค์เพื่อศึกษาการดำเนินการและโครงสร้างการควบคุมของระบบพลังงานสุริยะเข้มข้นร่วมกับระบบแรงกินอินทรีย์และระบบกักเก็บพลังงานความร้อนที่แตกต่างกัน ระบบกักเก็บพลังงานความร้อนที่ศึกษาคือระบบกักเก็บพลังงานความร้อนแบบสองถังกับระบบกักเก็บพลังงานความร้อนแบบบรรจุด้วยของแข็ง สถานะดำเนินการที่เหมาะสมของระบบสามารถหาได้ด้วยการจำลองระบบแบบสถานะคงที่ด้วยโปรแกรมจำลองระบบโปรทู ประสิทธิภาพทางความร้อนของกระบวนการที่ประกอบด้วยระบบพลังงานสุริยะเข้มข้นร่วมกับระบบแรงกินอินทรีย์เป็นฟังก์ชั่นวัตถุประสงค์ในการหาสถานะดำเนินการของระบบ ระบบพลังงานสุริยะเข้มข้นต้องใช้พื้นที่ในการรวบรวมพลังงานความร้อนประมาณ 75 ตารางเมตร เพื่อผลิตพลังงาน 18 กิโลวัตต์-ชั่วโมงต่อวัน ประสิทธิภาพทางความร้อนของกระบวนการที่สูงที่สุดคือ 7.05% การจำลองกระบวนการแบบพลวัตใช้โปรแกรมไดน์ซิมเพื่อศึกษาประสิทธิภาพของกระบวนการ จากการศึกษาพบว่าระบบกักเก็บพลังงานความร้อนต้องถูกปรับปรุงเพื่อให้โครงสร้างการควบคุมง่ายขึ้น ระบบกักเก็บพลังงานทั้งสองถูกเปรียบเทียบโดยประสิทธิภาพโดยรวมของกระบวนการ พบว่าระบบกักเก็บพลังงานความร้อนแบบบรรจุของแข็งมีประสิทธิภาพโดยรวมของกระบวนการสูงสุดเพียง 4.0% ซึ่งน้อยกว่าระบบกักเก็บพลังความร้อนแบบสองถังที่มีประสิทธิภาพโดยรวมของกระบวนการถึง 5.4%

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SITTIPORN VONGSILODKUL: Operation and control of concentrated solar power system integrated with thermal energy storage system. ADVISOR: ASSOC. PROF. SOORATHEP KHEAWHOM, Ph.D., 72 pp.

This research aims to study the operability and control stucture of small-scale concentrated solar power (CSP) system integrated with an organic Rankine cycle (ORC) and two different types of thermal energy storage (TES) systems: two tank and packed bed TES. The simulation was performed using a commercial steady-state simulator, PRO/II, to determine optimal operating conditions targeting at thermal efficeincy of CSP-ORC system. The solar field requires area around 75 m^2 to produce energy of 18 kWh which is above an average value power comsumption in residential section. The highest thermal efficiency of 7.05% is achieved. A commercial dynamic simulator, Dynsim, is used to perform dynamic simulation in order to investigate performance of the entire processes. A modified packed bed TES is introduced for simplicity in control structure. The overall efficiency of the process is used as performance index. The index is 5.4% for two tank TES as the heat loss is neglected. In case of packed bed TES, the maximum performance index of 4.0% was achieved, hence significantly lower than two tank TES.

Department:	Chemical Engineering	Student's Signature	....
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CONTENTS

Page

Page

LIST OF TABLES

LIST OF FIGURES

Page

Chapter 1
Introduction

1.1 Importance and reason

Solar energy is a clean and inexhaustible energy source for electricity production. One of the most promising technologies to capture solar energy is concentrated solar power system (CSP). CSP harnesses the energy by using mirrors to reflex a large area of solar thermal energy onto a smaller area. The concentrated thermal energy is transferred to a power conversion system by heat transfer fluid (HTF). After that, the power conversion system uses the thermal energy to drive a heat engine in order to generate electricity. However, a conventional CSP requires a large solar field to collect solar energy. This limitation make a conventional CSP difficult to apply in some regions. Thus, a small-scale CSP is preferable and focused in this research.

Commonly, CSP cooperates with a Rankine cycle in order to generate electricity. However, a conventional Rankine cycle using water as working fluid requires a large amount of thermal energy. Therefore, an organic Rankine cycle (ORC) is preferable to a small-scale CSP because ORC is a promising technology to convert low-grade heat source such as solar radiation into electricity. It uses organic fluid instead of water which requires lower energy to operate.

Despite its advantages, solar energy is inconsistent and can only be harnessed during daytime. In order to make CSP more cost effective, thermal energy storage (TES) is needed. TES allows solar energy from CSP to be dispatched continuously and can also store the energy for later use (Gil et al, 2010).

Due to the fact that TES is dynamic by its nature, the process suffers from operational and control problems. This characteristic connects directly to the performance of the electricity generation system. Recently, a dynamic simulation of electricity production using a commercial dynamic simulator was proposed (Manenti, F. and Ravaghi-ardebili, Z., 2013). The simulation was modeled from an actual concentrated solar power plant integrated with two-tank TES and power conversion system. The research analyzed not only the normal operation system but also the startup and shut-down operation of the system. Later, another dynamic simulation was introduced (Manenti et al, 2013). The research presented comparisons between two different types of TES adopted in a concentrated solar power plant: direct two-tank and direct single-tank TES. It was found that the direct two-tank TES was more flexible in terms of operation and control power generation. However, a comparison between the direct two-tank TES and packed bed TES using commercial simulator is still rarely seen.

This research aims to study dynamic behavior and control structure of a small-scale CSP integrated with an organic Rankine cycle (ORC) and different types of TES using commercial dynamic simulator, Dynsim. The performance of a two tanks TES and packed bed TES is compared and discussed.

1.2 Objective

1. To study operability and control structure of small-scale CSP integrated with an organic Rankine cycle (ORC) and different types of TES.
2. To optimize and compare the performance of two processes with different TES

1.3 Scope of work

1. A small-scale parabolic trough using Dowtherm™A as heat transfer fluid is selected as solar collector.
2. An organic Rankine cycle using acetone as working fluid is selected as power conversion system.
3. Dynamic simulation is simulated in commercial simulator Dynsim.
4. All controller are PI control using SIMC tuning method
5. Process with packed bed TES is control by 2 different control strategies. Performance of both process are compared with each other. Then, compare the better one with process with two tank TES.

1.4 Organization of thesis

Chapter 2 gather an information from previous works about process involving concentrated solar power system, organic Rankine cycle and thermal energy storage. The simulation back ground is also included in this chapter

Chapter 3 provides general knowledge of systems involved with this research including performance index to compare both process.

Chapter 4 introduce steady-state simulation to determine process operating condition and equipment sizing.

Chapter 5 describes how control structure of both processes is designed using the steps of plant wide control and dynamic simulation of all process.

Chapter 6 report results of steady-state and dynamic simulation including performance index of the process.

Chapter 7 summarize the details and work done in this research.

Chapter 2
Literature review

Solar energy is promising energy source for power production. Recently, a small-scale CSP integrated with TES and ORC has caught much attention. Many researches were conducted in order to study these systems in various aspects. Some useful data were applied in this research.

2.1 Concentrated solar power system (CSP)

CSP is an important component in solar power plant. It supplies thermal energy for power production process by converting solar energy into high temperature heat transfer fluid (HTF). Then, hot HTF is used to fuel a power conversion system in order to generate power. The concept of CSP technology is to concentrate the solar irradiation by concentrators (lens or mirrors) onto receivers. Currently, there are four CSP technologies: parabolic trough, linear Fresnel, solar tower and stirling dish. Among these technologies, parabolic trough is the most developed and widespread technology. Parabolic trough system converts solar energy to thermal energy by using parabolic mirrors as concentrators and reflects solar irradiation onto receivers which is located along focal line of the mirrors. The receiver is a steel tube that is enveloped with evacuated glass to prevent heat loss. In the receiver, HTF flows through the tube to collect the energy. Then HTF is used to boil working fluid in power conversion system to generate power.

Remi Dickes et al. (2015) reported on an improve correlation for heat loss in parabolic trough technology. The prediction of the previous correlations and the new one are compared based on commercial parabolic trough Soponova®. The new correlations yielded better fitting performance compared to the previous correlation but it limits only for small-scale CSP. In this research, heat loss correlations and technical specification of commercial CSP is used to optimize and simulate the process.

2.1.1 Heat transfer fluid (HTF)

HTF is a heat carrier to transfer thermal energy from CSP to power conversion system. Commonly, HTFs that used in conventional CSP are thermal oil and molten salt. However, molten salt has higher melting temperature and higher viscosity. As a result, CSP needs a large area of solar collector for the process to operate at high temperature in order to avoid solidification problem. Thus, thermal oil is preferable to small-scale CSP. Thermal oil offers heat stability and low viscosity in wide operational range of 12-400 C.

In this research, HTF is Dowtherm™A. It is a eutectic mixture of biphenyl ($C_{12}H_{10}$) and diphenyl ether ($C_{12}H_{10}O$). Richard L. More (2010) reported the physical and thermodynamic properties of synthetic oil Dowtherm™A in vapor and liquid phase.

2.2 Organic Rankine cycle (ORC)

ORC is a power conversion system that convert thermal energy into mechanical power. It is a Rankine cycle that uses organic substance instead of water as the working fluid. The organic fluid provides several benefits over water: low temperature, long service life and low maintenance cost [2]. This technology consist four components: pump, evaporator, expander and condenser. The saturated fluid from condenser is pumped to evaporator to receive heat from heat source resulting in high pressure working fluid. The working fluid is later enter the expander to produce useful power.

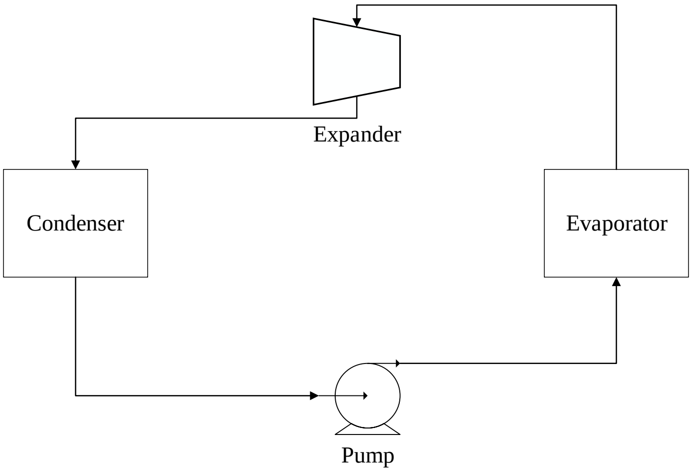

Figure 1. Concept of ORC

One of the most important factors to improve the efficiency of ORC is working fluid. Working fluid is the substance circulating in both Rankine cycle and ORC. In case of ORC, the working fluid is organic substance. ORC offers advantages over conventional Rankine cycle that uses water as working fluid: low temperature operating condition, long service life and low cost maintenance.

Ferrara et al. (2013) reported on the comparison of working fluid in an ORC integrated with CSP system including R134a, R245fa and Acetone. Several system configurations were studied: system with and without regeneration, system with and without superheating unit and system with an additional expander. The thermal efficiency of the system with different working fluid is compared. It was found that the maximum system efficiency can be achieved when the system operates with reheating unit, regeneration unit and additional expander by using acetone as working fluid. Therefore, acetone is selected to be working fluid in this research.

2.3 Thermal energy storage (TES)

TES is a key component in solar power plant. There are many types of TES available and thus their concepts are different. TES is an intermediate system between CSP and power conversion. It allows the energy from CSP to be dispatched with continuity and stores the heat transfer fluid (HTF) for later uses. TES also corrects the mismatch between supply and demand for energy.

Gil et al. (2010) studied on various TES technologies and reported a review on their concepts, classification, materials and modellization. According to Gil’s research, the most widespread TES technology is an active system such as direct two tanks TES. The advantage of direct two tanks TES is that it can store cold and hot HTF separately. The HTF from cold receives thermal energy from CSP and then flows to hot tank. The hot tank stores and release the HTF to ORC in order to generate power. However, the direct two tanks TES also has a disadvantage. It requires very high cost for material used as HTF and storage material. The alternative choice is other type of TES technology, passive TES.

Pauline Vitte et al. (2012) presented a simplified dynamic simulation of concentrating solar power plant with direct two tank TES using dynamic simulation program Dynsim. The research not only observed 24-hour dynamic behavior of storage tank but the startup procedure as well. The dynamic model can be adapted in this research to understand the behavior of the system and design the storage tank.

Mario Cascetta et al. (2014) investigated on transient behavior of packed-bed TES using different HTF: air, oil and molten salt. The storage consists of spherical particles of commercial alumina. The available data of solid bed properties and equation for sizing the TES can be applied in this research. The research concluded that oil and molten showed good performance in charging and discharging after continuous operation while air reduced its capacity to store energy. However, molten salt has a solidification problem at low temperature. As a result, the system has to operate at high temperature. Thus, oil is more suitable HTF for a TES system integrated with small-scale CSP.

Zanganeh, G., et al. (2014) investigated the impact of operational and design parameters on the performance of TES system using dynamic simulation. The dynamic model was validated with experimental result and then applied to design industrial-scale thermal storage unit. The equation for calculating efficiency of TES is applied in this research in order to identify the suitable TES system for small-scale CSP integrated with ORC.

2.4 Dynamic simulation

Flavio Manenti and Zohreh Ravaghi-Ardebili (2013) introduced a simplified dynamic simulation of Archimede concentrating solar power plant by using commercial dynamic simulation program to study dynamic behaviors and control of the process. The plant is a combination of parabolic trough CSP and two tanks TES. The layout of the plant in commercial dynamic simulation program can be adapted in this research.

Zohreh Ravaghi-Ardebili et al. (2013) investigated on dynamic simulation of solar power plant with different TES, direct two tanks and direct single tank, by using dynamic simulation program. The simulation was performed based on available data from an actual solar power plant. A comparison between two TES technologies was proposed. It was found that two tanks TES is more flexible to provide power generation and control. However, power generation of the process is affected by solar irradiance and not suitable for residential application. Thus, this research aims to compares the process with two tank thermal energy storage and packed bed thermal energy storage that can provide stable power generation at power demand.

Angelini et al. (2014) studied the dynamic simulation of solar power plant with packed bed TES. The dynamic model was validated to an available experimental data. Then, the dynamic model of packed bed was applied for the solar power plant with two tank TES to compare both TES performance while the management of CSP and ORC remained the same. The performance index was overall efficiency of TES. It was found that packed bed TES provided 65% of overall efficiency while the overall efficiency of two tank TES remained 100% if the heat loss was neglected. The research also indicated that CSP and power conversion system did not operated at optimum working conditions when two tank TES was replaced by packed bed TES.

In conclusion, this research aims to study and compare two tank TES to packed bed TES integrated with small-scale CSP and ORC using commercial dynamic simulation. The CSP technology is parabolic trough that uses Dowtherm™A as HTF. The ORC using acetone as working fluid is selected as power conversion system. The simplified dynamic simulation layout is adapted from Manenti, F. and Zohreh's research using dynamic simulation program Dynsim. The dynamic behavior of the process is observed through 24-hour simulation. The performance index to compare both TES system is overall efficiency.

Chapter 3

Fundamental knowledge and theory

3.1 Concentrated solar power system

Concentrated solar power system (CSP) produce heat by using mirrors or concentrators to concentrate sunlight onto receivers where the thermal energy is transferred to heat transfer fluid (HTF). This technology can be applied to produce power for electricity generation by thermodynamic cycle. Currently, there are four types of CSP technologies including parabolic trough system, linear Fresnel reflector system, solar tower system and dish-strirling system.

Parabolic trough system

Parabolic trough system is the most developed and widespread of all CSP technologies. It consists of parabolic mirrors to concentrate sunlight onto receiver tubes along the focal line in order to raise HTF’s temperature inside the receiver tubes.

Linear Fresnel reflector system

Linear Fresnel reflector system is similar to parabolic trough system but simple compared to parabolic trough design. This technology uses arrays of flat mirror to reflect sunlight onto stationary receiver.

Solar tower system

Solar tower system uses numbers of dual-axis individual mirrors (heliostat) to track and concentrate sunlight onto receiver on top of the tower in order to raise HTF’s temperature. The temperature of HTF can reach from 500 °C to over 1000 °C.

Dish-Stirling system

Dish-Stirling system is small unit compared to other CSP technology. It consists of a large dish-shape mirror that concentrate sunlight onto a receiver at the focal point of the dish to heat HTF for power generation by using Stirling engine while other technologies use Rankine cycle.

After consider all options, parabolic trough system and dish-Stirling system are suitable technologies for small-scale CSP. However, parabolic trough technology has an advantage. Dish-Stirling system employs Stirling engine to generate electricity while parabolic trough cooperates with Rankine cycle as power conversion system. Thus, parabolic trough can be improved by the addition of thermal energy storage system.

3.1.1 Principle and dynamic model of small-scale parabolic trough system

A unit of parabolic trough technology consists of parabolic reflectors and receiver tubes. Parabolic reflectors concentrate sunlight onto heat absorber tube at the focal line of the reflector. The absorber tube is a special tube which HTF flow though to receive thermal energy. Then, hot HTF is used to evaporate working fluid in power conversion system for power generation.

Parabolic reflector

A parabolic reflector has one reflecting surface which made of metal foil or segments of curve mirror. It also has one-axis tracking system to track the sun position. The mirrors usually coated with back-silvered white low iron glass to achieve high reflectivity.

Heat absorber tube

An absorber tube is special tube which located along the focal line of parabolic reflector. It is a steel absorber tube that enveloped with evacuated glass to reduce heat loss.

Heat transfer fluid

Heat transfer fluid (HTF) is substance that carry thermal energy from CSP to other unit in solar power plant. Currently, common fluid for HTF are synthetic oil and molten salt. However, molten salt requires vast area of solar field to keep the fluid at high temperature to avoid solidification problem. This makes synthetic oil suitable for small-scale CSP. Synthetic oil in this research is Dowtherm$^{\copyright}$A. It is eutectic mixture of 26.5% of biphenyl ($C_{12}H_{10}$) and 73.5% of diphenyl ether ($C_{12}H_{10}O$). It can operates efficiently at maximum temperature of about 400 °C which is suitable with temperature range of small-scale CSP.

Dynamic model of parabolic trough

The dynamic model of parabolic trough to predict its HTF temperature is based on one-dimensional discretization of receiver tube. As illustrated in Figure 2, heat collection in each cells are discretized in N cells of constant volume.

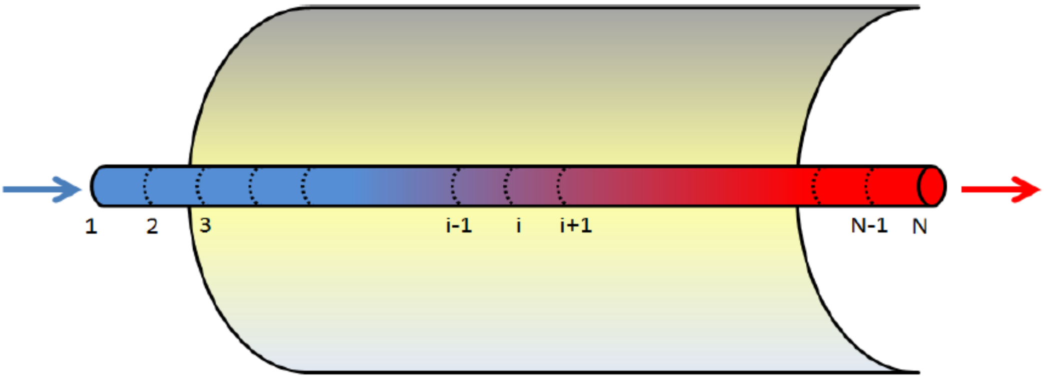

Figure 2. One-dimensional discretization along receiver tube

However, there are only 2 cells in this research, in and out of receiver tubes. The dynamic model can be explained by equation (1)

$$T_{out} = T_{in} + \frac{\dot{Q}_{abs}}{\dot{m} C_{p,HTF}} \tag{1}$$

Where T_{in} and T_{out} are temperature of HTF in and out of receiver tube respectively. $\dot{Q}_{abs}$ is net heat power absorbed in receiver tube. $\dot{m}$ is mass flow rate of HTF and $C_{p,HTF}$ is specific heat capacity of HTF.

The net heat power absorbed in receiver tube, $\dot{Q}_{abs}$, was derived by Forristal [13]. This approach account for convective, conductive and radiative heat exchanges occurring between the receiver tubes and surrounding. It was validated with experiments and widely used in many literatures. However, solving all the heat exchanges in the receiver tubes is very complex and take long time for calculation. A new approach to increase the speed of calculation is proposed. This method is to calculate the heat losses of receiver tubes, $\dot{Q}_{loss}$, by determine the correlation for linear heat losses HL. There are many literature that study on HL to determine correlation of this variable. Remi

Dickes et al. reported on the equation of heat losses which can be explained by equation (2).

$$
\begin{aligned}
HL = {} & a_0 + a_1(T_{HTF} - T_{amb}) + a_2(T_{HTF} - T_{amb})^2 + DNI\cos(\theta)(a_3T_{HTF}^2 + a_4\sqrt{v_{wind}}) \\
& + a_5T_{HTF}^3 + v_{wind}(a_6 + a_7(T_{HTF} - T_{amb})) + \sqrt{v_{wind}}(a_8 + a_9(T_{HTF} - T_{amb}))
\end{aligned} \tag{2}
$$

Where T_{HTF} is temperature of HTF, T_{amb} is ambient temperature, DNI is direct solar irradiance, θ is incidence angle and v_{wind} is wind velocity. However, information on wind speed of Thailand is difficult to come by. Therefore, the effect of wind speed in equation (2) is neglected. The equations concerning $\dot{Q}_{abs}$ are explained by equation (3) – (5).

$$\dot{Q}_{abs} = \dot{Q}_{sun} - \dot{Q}_{loss} \tag{3}$$

$$\dot{Q}_{sun} = DNI \cdot \cos(\theta) \cdot \eta_{opt} \cdot W_{PTC} \cdot \Delta x \tag{4}$$

$$\dot{Q}_{loss} = HL \cdot \Delta x \tag{5}$$

Where $\dot{Q}_{sun}$ is effective solar power reflect, W_{PTC} is receiver tube aperture, η_{opt} is overall optical efficiency, ρ_{PTC} is mirror reflectivity, $\tau_{envelop}$ is envelop transmittance, α_{tube} is tube absorptivity and Δx is receiver length. The constant inputs are based on the actual commercial parabolic trough unit Soponova® and shown in table 3.1. The heat loss coefficient is shown in Table 3.2

Table 3.1 Soponova® CSP collector specification

Properties	Value	Units
Receiver aperture	1.425	m
receiver length	3.657	m
Tube inner diameter	23.26	mm
Tube outer diameter	25.4	mm
Envelope inner diameter	51	mm
Envelope outer diameter	55	mm
Overall optical efficiency	0.89	-

Table 3.2 Heat loss coefficient

Coefficient	Value
A0	20.62
A1	-0.289
A2	0.001472
A3	2.24E-08
A4	0.001198
A5	0.001403
A6	1.045
A7	-0.03043
A8	-8.481
A9	0.2073

The efficiency of CSP η_{CSP} in equation (6) is defined as a ratio between heat input to HTF and thermal energy from solar irradiance.

$$\eta_{CSP} = \frac{\dot{Q}_{CSP \rightarrow HTF}}{\dot{Q}_{sun}} = \frac{\dot{Q}_{sun} - \dot{Q}_{loss}}{DNI \times A_a} \tag{6}$$

Where $\dot{Q}_{CSP \rightarrow HTF}$ is thermal energy absorbed by HTF and A_a is area of CSP aperture.

3.2 Power conversion system

Power conversion system is the system that convert the thermal energy from CSP into power for electricity generation. Most CSP technology cooperate with Rankine cycle as power conversion except dish-Stirling system that can only operates with Stirling engine. Rankine cycle is thermodynamic cycle that consist of four main component: pump, evaporator, expander and condenser. Figure 3 illustrates T-S diagram of simple Rankine cycle.

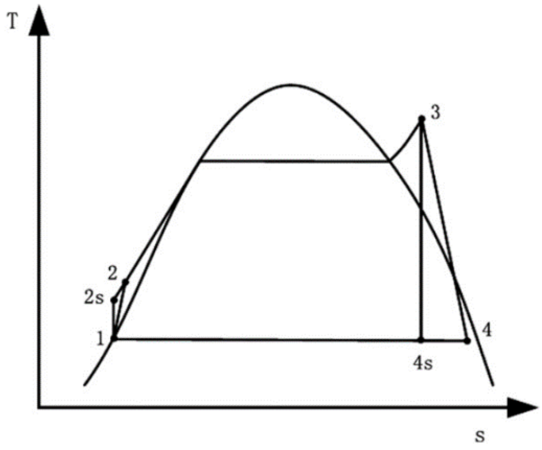

Figure 3. T-S diagram of simple Rankine cycle

Process 1-2: Actual compression by pump. The working fluid in liquid phase is pressurized to high pressure.

Process 1-2s: Isentropic compression by pump

Process 2-3: Isobaric heat addition in evaporator. The working fluid is evaporated in evaporator at constant pressure to superheated vapor.

Process 3-4s: Isentropic expansion in expander.

Process 3-4: Actual Expansion in expander. Superheated vapor enter the expander to extract power for electricity generation.

Process 4-1: Isobaric heat rejection in condenser. The working fluid is condensed in condenser and flow back to pump to repeat the cycle.

The advantage of using Rankine cycle instead of Stirling engine as a power conversion system is that the process can be improve with thermal energy storage to make the system more cost effective. However, Rankine cycle with water as working fluid requires high pressure and temperature to prevent two phase fluid in expander which results in expander damage. Thus, the cycle need large solar field to collects the heat to operate. A new approach is to change the working fluid to lower boiling fluid that yield high efficiency in power generation. An organic Rankine cycle (ORC) is an interesting alternative.

Organic Rankine cycle

ORC uses organic fluid that has low boiling point as working fluid instead of water. Besides, most of organic fluids are dry fluid which has positive slope saturated curve. As illustrated in Figure 4, the benefit of using dry instead of water is that the cycle requires less heat to operate since the working fluid does not need to be superheated to prevent expander damage. This indicate that working fluid is crucial factor in ORC. To achieve high efficiency, the working fluid needs to be selected carefully.

Working fluid

There are many organic fluids that suitable for ORC in specific range. Since ORC can operates in wide temperature range from less than 100°C to over 500°C, the working fluid selection should be handle carefully. Nowadays, the common working fluids applied in low temperature ORC are refrigerants. Among the refrigerants, R134a and R245fa seem to be suitable choice for low temperature ORC. However, a recent study shows that acetone outperform the mentioned refrigerants in terms of power generation. Therefore, acetone is chosen to be working fluid for ORC in this research.

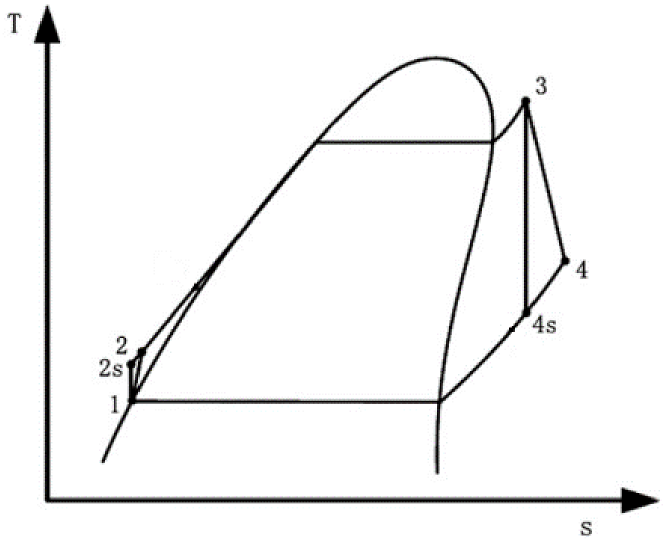

Figure 4. T-S diagram of ORC with dry fluid

The ORC efficiency η_{ORC} in equation (7) is a ratio between work from expander and heat input of ORC system.

$$\eta_{ORC} = \frac{\dot{W}_{net}}{\dot{Q}_{ORC}} = \frac{(h_{in,Ex} - h_{out,Ex})}{(h_{in,Ev} - h_{out,Ev})} \tag{7}$$

Where $\dot{W}_{net}$ is net power output, h_{Ex} is enthalpy across an expander and $\dot{Q}_{ORC}$ is thermal energy input of ORC.

3.3 Thermal energy storage

Thermal energy storage (TES) is a promising technology to be integrated with CSP to make the system more cost effective. It improves process availability by correcting a mismatch between supply and demand electricity. Thus, the process is more flexible. As illustrated in Figure 5, TES technologies are divided into two concepts: active and passive storage system.

In active system, the storage medium itself circulates within the system to transfer the energy into storage material. This technology uses one or two tank to be storage media. Active TES is divided into two categories, direct and indirect system. In case of direct system, HTF from CSP and the storage medium is the same substance while an indirect system uses another substance as storage medium.

A passive system operates with different concept from an active system. In passive system, the HTF from CSP pass through the storage media only for charging and discharging a solid material. The storage medium itself do not circulate. HTF collects thermal energy from CSP and pass it through storage medium during charging. During discharging period, HTF collects the heat from solid material to fuel the power conversion system.

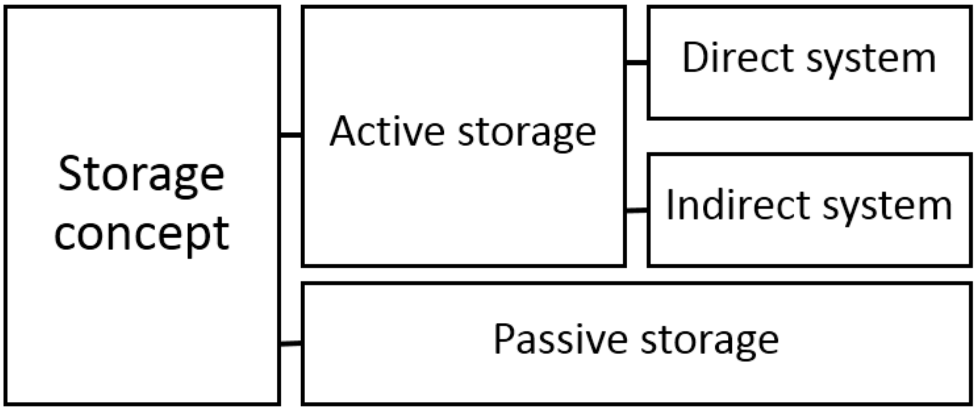

Figure 5. Classification of thermal energy storage system

3.4 Process overview

The whole process consists of three components including CSP, TES and ORC. Figure 6. illustrates overall solar power plant with two tank TES. The cold HTF from cold tank pass through parabolic trough system to receive thermal energy. The hot tank stores and dispatches the high temperature HTF to boiler in order to transfer the heat to working fluid in ORC. After receiving heat from HTF, the working fluid flows to an expander. Then, the working fluid is expanded to produce power.

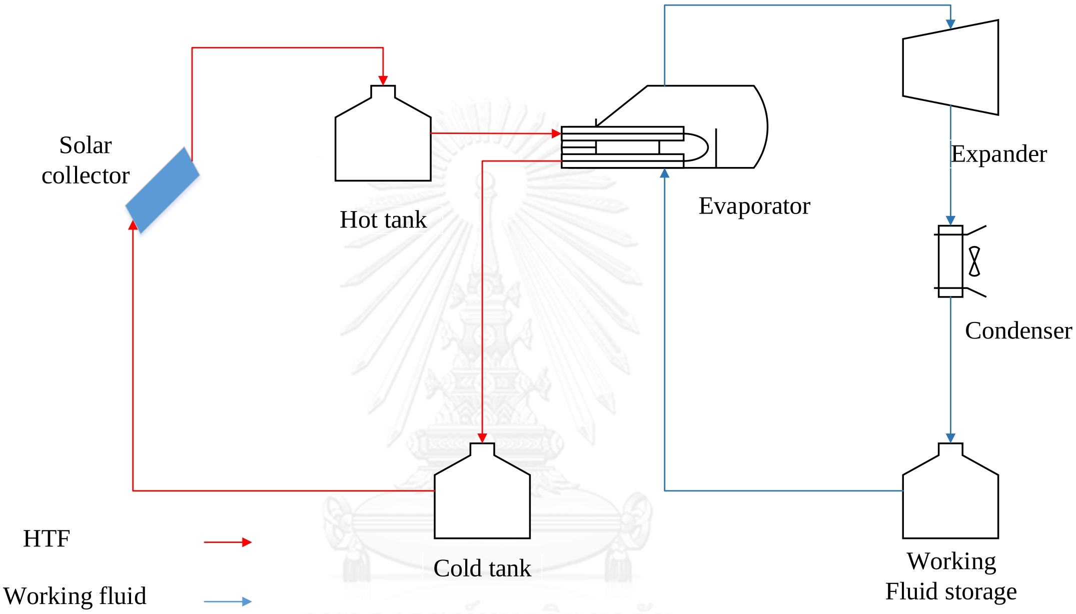

Figure 6. Overall solar power plant with two tank TES

In case of packed bed TES, the concept is different. Figure 7. illustrates overall solar power plant with packed bed TES. This system operates in two modes depending on sunshine availability: charging and discharging mode. During sunshine period, the system is in charging mode. Hot HTF from CSP flows to ORC to generate power while the excess HTF flows into packed bed TES from the top to transfer the heat into solid storage medium. Conversely, the system switches to discharging mode during the night. HTF enters packed bed TES from the bottom to collect thermal energy from solid storage medium. Later, hot HTF flows through the boiler to transfer the heat to working fluid in ORC.

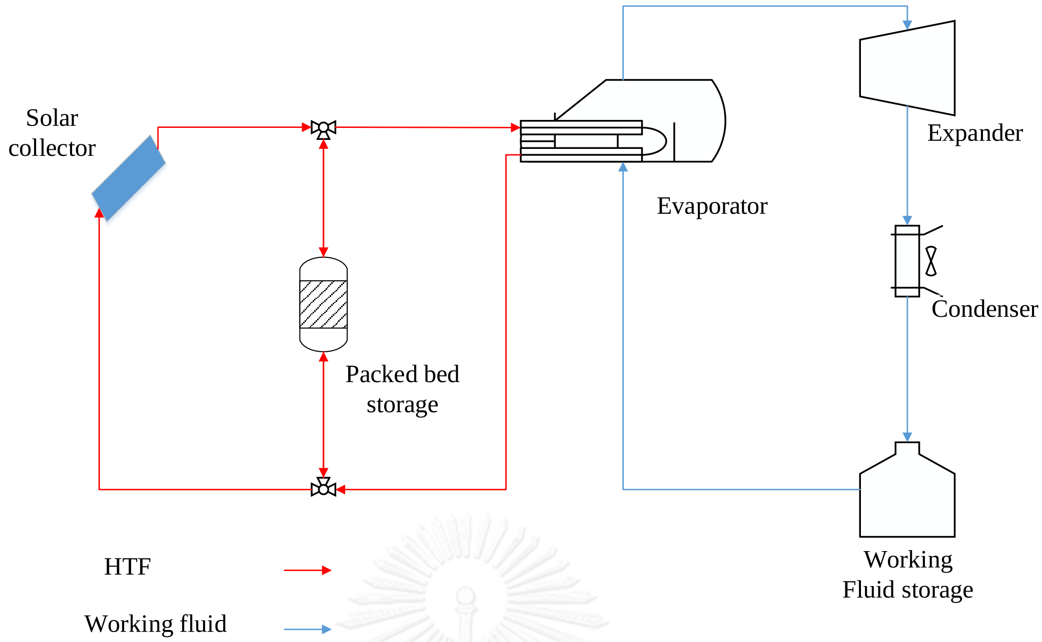

Figure 7. Overall solar power plant with packed bed TES

3.5 Efficiency calculation

To identify a suitable TES system for the process, performance of both systems should be taken into account. Efficiency of all three systems, CSP, ORC and TES, should be taken into account.

3.5.1 Thermal energy storage efficiency

The two tank TES system in the process is replaced by packed bed TES system of with the same thermal capacity. To determine which TES system is better, the overall efficiency of both TES needs to be defined. Charging and discharging are always remains at 100% for direct two tank TES system, while they are always below 100% in case of packed bed TES system.

In packed bed TES case, TES operates in two modes, charging and discharging. The efficiency of TES in both modes are calculated separately. The charging efficiency is defined as the ratio of energy stored in solid bed at the end of the cycle to the net input.

$$\eta_{Charging} = \frac{E_{Stored}}{E_{Inflow,ch} - E_{Outflow,ch}} \tag{8}$$

Where the stored energy is calculated by $E_{Stored} = \sum_{i=1}^{N}(1-\varepsilon)\rho_s V_i((e_{s,i})_{t_f} - (e_{s,i})_{t_0})$ while t_0 and t_f are temperature at start and end the charging phase. i denotes a layer of solid bed in TES. The variable e is the internal energy of solid bed. The inflow and outflow energy can be calculated by equation (9) and (10):

$$E_{Inflow,ch} = \sum_{t=0}^{t_{charing}} h_{f,in}^{t} \dot{m}^{t} \Delta t \tag{9}$$

$$E_{Outflow,ch} = \sum_{t=0}^{t_{charing}} h_{f,N}^{t} \dot{m}^{t} \Delta t \tag{10}$$

Where h_f^t is the specific enthalpy of fluid and $\dot{m}^t$ is mass flow rate of fluid. The discharging efficiency is defined as the ratio of useful recovered energy during discharging phase to the stored energy.

$$\eta_{Discharging} = \frac{E_{Outflow,dis} - E_{Inflow,dis}}{E_{stored}} \tag{11}$$

The $E_{Outflow,dis}$ and $E_{Inflow,dis}$ can be calculated the same way of the charging phase. Then, the overall efficiency of TES can be calculated by equation (5)

$$\eta_{Overall} = \eta_{Charging}\eta_{Discharging} \tag{12}$$

Chapter 4
Steady-state simulation

Designing of control structure requires optimization to determine the optimal operating condition. Simulation is required to simulate the process so that the result can be used to design and improve the process. In commercial solar power plant, inconsistency of solar irradiance has a significant influence on profit of the plant. Real time optimization should be applied to determine set-point for control loop in dynamic process. However, real time optimization requires complex dynamic models and constraints involved the system. Thus, it requires long and heavy on-line computational time which is not suitable for process in this research that focus on produce power for household application. In this research, there are 2 simulations including steady-state simulation and dynamic simulation. The steady-state simulation is used to determine optimal operating condition and sizing equipment of the process while dynamic simulation is used to study the process dynamic behavior.

4.1 Steady-state simulation

Steady state simulation is used to duplicate system with constant parameter and variable. Since TES system is dynamic in its nature, it will not be include in this section. The objective of this simulation is to determine operating condition which yield maximum overall steady-state efficiency. This simulation consist of 2 systems: CSP and ORC

4.1.1 Design of ORC system

ORC is the system that produce power from thermal energy collected by CSP. Its operating condition is a very important factor to the overall efficiency. ORC consists of pump, boiler, expander and condenser. All of the mentioned equipment can be easily modeled by using PRO/II. The operating condition is determined by using the optimizer provided by the steady-state simulator.

The boiler in ORC is modeled by a simple heat exchanger. The heat exchanger outlet is specified by the temperature rise above fluid dew point because the fluid outlet of the boiler is saturated fluid or slightly superheated. Thus, the heat exchanger is specified to rise the fluid temperature above its dew point by 1 ^{0}C.

The expander in this research is modeled after commercial expander E15H022A-SH distributed by Air squared incorporation. In table 1, many characteristic of the expander is shown. However, the expander model can be specified by 1 specification at a time. Pressure ratio is the only specification that is specified for expander model in the simulation. Thus, the expander is specified by pressure ratio of 0.29 with the adiabatic efficiency of 0.7, the maximum adiabatic efficiency of the commercial expander.

Table 4.1 The characteristic DATA of E15H022A-SH scroll expander

Properties	Value	Unit
Nominal output	1	kW
Pressure ratio	0.29	
Displacement	12	cm^3/rev
Max speed	3600	RPM
Max inlet pressure	13.8	bar
Max inlet temperature	175	^{0}C
Ambient temperature range	-20-40	^{0}C

In case of power production, the average electricity consumption for 1 individual household is 12 kWh per day. It is used as the power production of expander to determine the working fluid flow rate. The working fluid temperature is initially 30 °C.

The optimizer is used to determine the optimal operating condition for the highest overall efficiency. This model can be specified by 1 objective function with various vary variable and constraints. The objective function of this steady-state simulation is the maximum overall efficiency which is mentioned before in the previous chapter. The constraints are heat duty collected by CSP, the power production range of the expander and the operating condition range (pressure). Figure 8 show the schematic of ORC in steady-state simulation and the specification of optimizer.

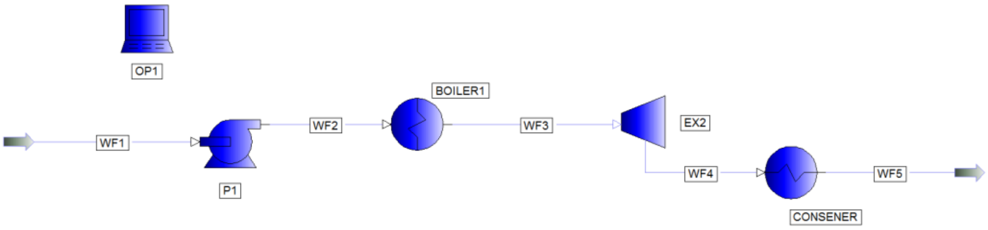

Figure 8. Schematic of steady-state simulation for ORC optimization

The heat duty range of the boiler is calculated by multiplying direct normal irradiance (DNI) by the area of solar aperture which is mentioned in Table 3.1. The minimum value of 15 MJ/m^2 solar irradiance in autumn is used as the DNI to determine area of CSP aperture. The area of aperture is assumed to be in range of 50-100 m^2. Initial specifications of equipment is shown in Table 4.2

Table 4.2 Specification of equipment in ORC steady-state simulation

	Value	Unit
Stream WF1		
Component	Acetone	
Flow rate	1.132	kg-mol/°C
Temepratures	30	°C
Pressure	1	bar
Pump P1		
Pressure rise	0	bar
BOILER1		
Cold product temperature rise above dew point	1	°C
Expander EX2		
Pressure ratio	0.29	
Adaibatic effeiceincy	70	Percent
CONDENSER		
Temperature below bubble point	2	°C

4.1.2 Design of CSP system

CSP is the system that collect heat input for the whole process. It plays key role in steady-state optimization of the process. It limits the maximum power that ORC can produce. In PRO/II, pipe model is suitable to represent CSP. The thermal energy collected by CSP is specified by heat duty which is determined from the previous section. However, the heat duty that obtained from the previous section is the heat input that ORC uses to operation for 24 hours while the solar available is assumed to be only

8 hours. Thus, the optimal total heat duty obtained from the previous optimization is multiplied by 3.

Not only steady-state simulation for CSP can determine heat duty that process require to operate, it also determine dead time as well. Dead time is an amount of time that process take to change response when there is change in input. Since CSP is very large system, process dead time might be large which is important to tuning calculation for control system. Dead time of CSP can be determine by equation (13).

$$\theta = \frac{\Delta x}{v_{HTF}} \tag{13}$$

Where θ is dead time, Δx is receiver length and v_{HTF} is HTF velocity.

4.1.3 Design of CSP-ORC system

The combination of CSP and ORC is important to design the process for dynamic simulation. For instances, the volume of thermal energy storage can be determined by the volumetric flow rate of HTF. This section aims to determine not only the operating conditions in CSP system such as HTF flow rate and temperature but also size of TES as well.

The CSP-ORC steady-state simulation configuration is illustrated in Figure 9. The optimal condition of ORC from previous section is used to specify the equipment in ORC. A heat exchanger is added to preheat working fluid before it enters boiler. The optimizer is used to determine optimal operating conditions of CSP. Equation (2)-(5) show that heat loss from CSP receiver tubes depend on HTF temperature. Thus, the objective function of this simulation is to minimize the HTF temperature at CSP outlet. HTF temperature range is between 100 °C (slightly higher than working fluid dew point) to 175 °C. HTF flow rate is varied variable. The initial temperature of HTF should be more than 50 °C (initial temperature of working fluid).

A splitter is added to the system to divided HTF flow to separate system: ORC and TES. The charging period of TES is assumed to be 8 hours per day. Thus, the ratio of HTF flow rate to ORC and HTF flow rate to TES is 1:3. All specifications of steady-state simulation are shown in Table 4.3.

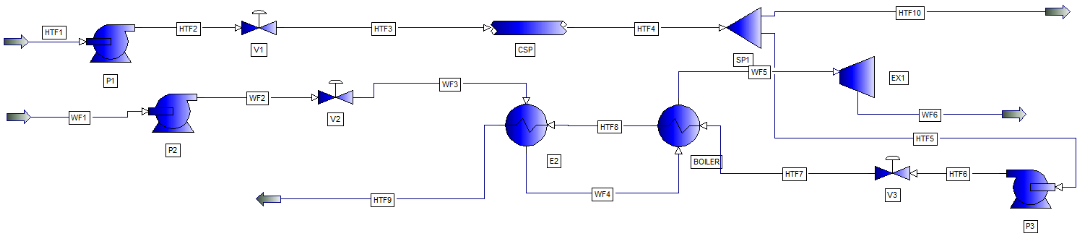

Figure 9. CSP-ORC process in steady-state simulation for CSP optimization

Table 4.3 Specifications for equipment in steady-state simulation

	Value	Unit
Stream HTF1		
Component	0.265/Biphenyl 0.735/Diphenylether	
Flow rate	5	kg-mol/°C
Temperature	35	°C
Pressure	3	bar
Stream WF1		
Component	Acetone	
Flow rate	1.132	kg-mol/°C
Temperature	50	°C
Pressure	1	bar
Pump P1		
Outlet pressure	4	bar
Pump P2		
Outlet pressure	8	bar
Valve V1		
Pressure drop	3	bar
Valve V2		
Pressure drop	4.5	bar
Valve V3		
Pressure drop	3	bar
Heat exchanger CSP		
Duty	121	MJ/hr
Heat exchanger E2		
Cold product temperature rise below bubble point	55	°C
Heat exchanger BOILER		
Cold product temperature rise above dew point	1	°C
Splitter SP1		
Stream HTF10 flowrate/HTF5 flowrate	0.65	
Expander EX1		
Pressure ratio	0.29	
Adiabatic efficiency	70	Percent

However, there are 2 control strategies for process with packed bed TES. The objective function of optimizer is changed to maximize the temperature difference across TES.

4.1.4 Steady-state simulation scenario

The optimal operating conditions are determined by using the minimum solar irradiance. However, sizing of equipment in the process is different. For example, TES volume should be able to store HTF in the hottest day (highest solar irradiance). The steady-state simulation for equipment sizing should be simulated under the assumption of the highest solar irradiance. As for ORC case, the maximum solar irradiance cause the maximum heat duty which results in maximum expander power production. The maximum power production of the commercial scroll expander in this research is limited to 1 kW. HTF and working fluid flow rate are varied to match the process operating conditions.

Chapter 5

Control structure and dynamic simulation

Main objective of control structure design is to answer these basic questions: what variable should be controlled, what variable should be measured, what variable should be manipulated and how those variable interconnect. The process in this research focuses on power generation for individual household which power demand is not constant. Thus, the control system must be able to ensure that the process can response to power demand changes. In this chapter, the control structure that used in conventional solar power plant will be discussed along with the alternative control structure that is designed in this research.

5.1 Conventional solar power plant control structure

Similar to small-scale solar power plant, a conventional solar power plant consists of 3 systems including CSP, TES and power conversion system. However, a solar field in conventional solar power plant requires large area to collect thermal energy from the sun. Some variables are difficult to control at the specific set point due to large dead time and uncertainty of solar irradiance. Most conventional solar power plant allow power production to change according to solar availability by controlling HTF flow rate in the process regardless of solar irradiance at the time. Some solar power plant uses HTF that has high freezing point to reduce the cost. Temperature of HTF needs to be kept above freezing point to avoid HTF solidification. Figure 10 and 11 show controlled variable of process with two tank TES and packed bed TES, respectively. However, the process in this research focuses on the small-scale CSP system integrated with ORC and TES for power production in individual household. Thus, the process must supply power to satisfy power demand at the time regardless of solar availability. The control structure is designed to produce the power to satisfy power demand under inconsistency of solar irradiance.

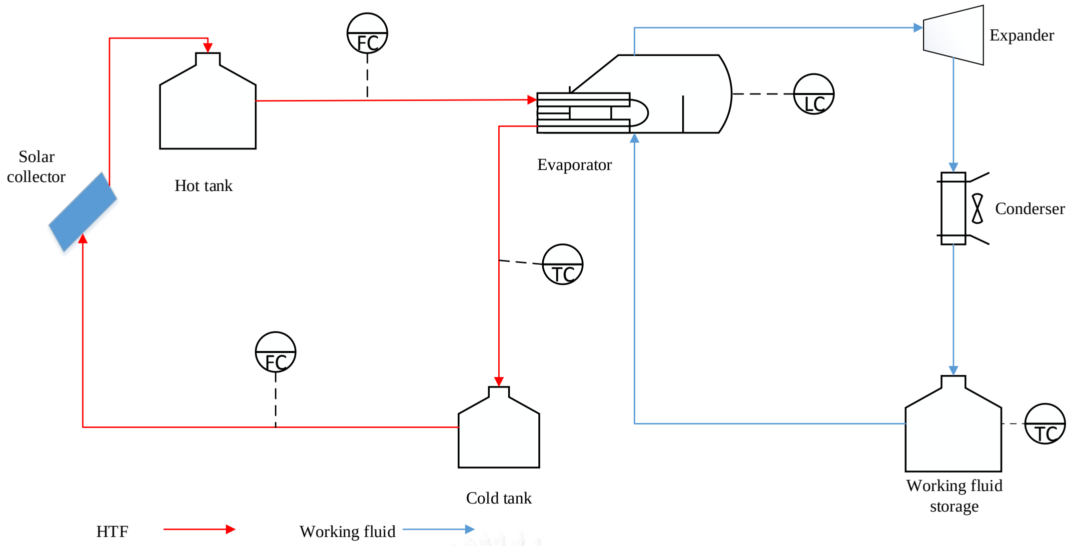

Figure 10. Controlled variable for process with two tank TES in convention solar power plant

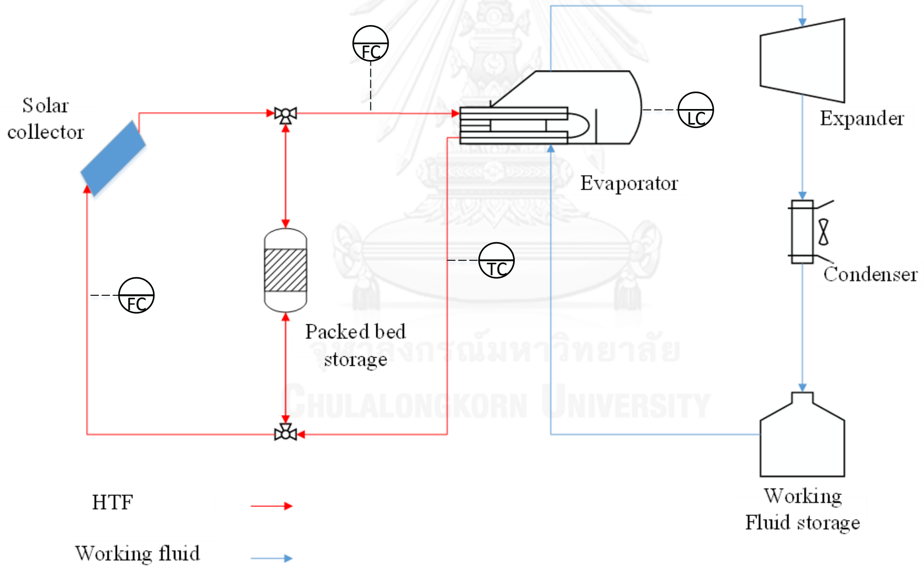

Figure 11. Controlled variables of process with packed bed TES in conventional solar power plant

As illustrated in Figure 10, cold tank supplies HTF to collect thermal energy at CSP during the day. HTF flow rate from cold tank is controlled at specific set point because large solar field provides difficulty for controlling some variable such as HTF temperature. Hot HTF is stored in hot tank and then is dispatched to supply thermal energy to ORC by controlling HTF flow rate at hot tank outlet. The temperature controller at evaporator outlet is to keep temperature of HTF above its freezing point.

Level controller is used to prevent emptying or overfilling of working fluid inside evaporator. During the night, cold tank supply no HTF to CSP because there is no solar irradiance while other controllers operate the same as it does during the day.

In case of process with packed bed TES, the process operates in 2 modes, charging and discharging mode. In charging mode, similar to process with two tank TES, flow control is used to control HTF flow rate at CSP inlet to harness thermal energy during the day. Then, hot HTF from CSP is divided into 2 stream. The flow controller at evaporator inlet is to control the amount of thermal energy fed to ORC by controlling HTF flow rate while stores the rest of thermal energy from another HTF stream into packed bed TES. Temperature controller at evaporator outlet is to keep HTF's temperature above its freezing point. During the night, process manually switches to discharging mode. HTF from evaporator flow upward to collect thermal energy from packed bed TES instead of CSP. Flow controller at CSP inlet is closed while the flow controller at evaporator inlet operates the same as it does during the day.

5.2 Skogestad procedure for control structure

Control system can be categorized into 2 layers: optimization layer and control layer. Controlled variable set point is calculated in Optimization layer then implemented by control layer to achieve the desired controlled variables. Control system hierarchy is illustrated in Figure 12.

As illustrated in Figure 12, control layer is divided into 2 parts: fast regulatory control (stabilization) and slow supervisory control (operational objective). The regulatory control purpose is to make sure that the process operates while supervisory control is to make the process operates as intended.

One of the most successful method to design the control structure is proposed by Sigurd Skogestad (S. Skogestad, 2004). It consists of 7 steps which can be divided into 2 parts: top-down and bottom-up part.

This method is categorized into 2 parts: top-down (step 1-4) and bottom-up part (step 5-7). Top-down part involves with defining operation objective, degrees of freedom and optimal condition while bottom-up part concentrate on control layers structure.

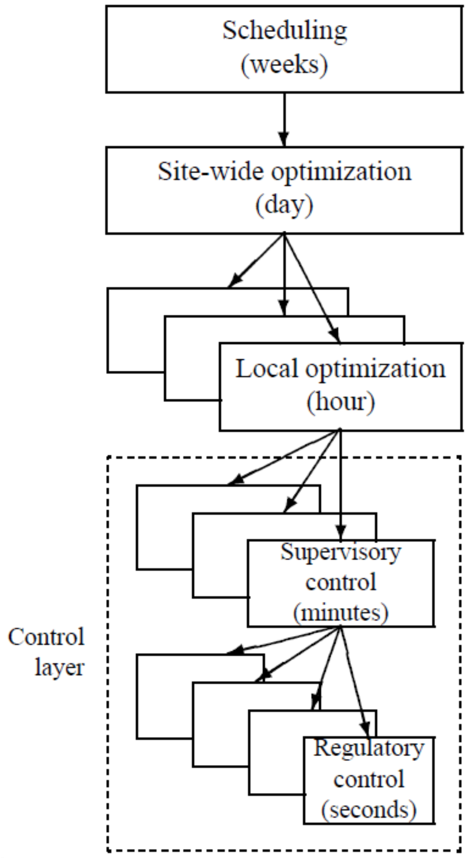

Figure 12. Control system hierarchy

5.2.1 Step 1: Define operational objective and constraints

Commonly, operational objective of power generation in convention solar power plant is either to minimize cost or to maximize profit. However, the process in this research focuses on power generation for application in individual household without connection to the grid. Thus, the operational objective is to generate as much power as the process could with the limited available solar energy. Since the efficiency of CSP is mainly depended on the specification of CSP equipment and HTF, the key system to maximize the thermal efficiency is ORC. ORC can operate at many states such as saturated, superheated and super critical state. However, it yields more thermal efficiency as saturated vapor than others. Thus, the operation objective is to maximize the thermal efficiency of ORC by using the saturated working fluid but still satisfies the power demand for an individual household in the limited solar energy.

The optimum operating condition is based on steady-state optimization to maximize the overall efficiency of the process. Thus, TES which is dynamic by its nature is not included in this section and will be discussed later.

$$\eta = \eta_{ORC} \times \eta_{CSP} \times \eta_{TES} \tag{14}$$

$$\max \eta \tag{15}$$

Subject to these constraints:

$$DNI \leq 30\,\text{MJ/m}^2$$

$$50 \leq A_a \leq 100\,\text{m}^2$$

$$0.5 \leq \dot{W}_{net} \leq 1\,\text{kW}$$

5.2.2 Step 2: Identify controlled variables, manipulated variables and degree of freedoms

a.) Controlled variable: A controlled variable is an output variable that needed to be controlled in order to achieve operational objective and safety purposes.

Process in this research focuses on produce power to satisfy power demand regardless of solar irradiance inconsistency. The operational objective requires efficiency of all systems including CSP, TES and ORC. The efficiency of these system is mainly depended on operating condition of the process such as pressure and temperature. As mentioned conventional solar power plant section, the control strategy in conventional solar power plant is difficult to control some variables such as temperature and pressure of HTF under disturbance from solar irradiance. Thus, a new control strategy need to be designed.

The system that has most direct effect in power production is ORC. An expander in ORC is a mean to convert thermal energy into power for electricity generation. The amount of power that expander can produce not only depends on operating condition of working fluid but working fluid flow rate as well. These variables affects an expander speed which usually used for power production measurement. An expander speed needs to be tightly controlled in order to satisfy power demand and expander limitation. From equation (7), efficiency of ORC depends on enthalpy across expander. Evaporator pressure needs to be tightly controlled to maintain enthalpy inside at expander inlet. In conventional solar power plant, HTF temperature at evaporator outlet is controlled to avoid HTF solidification. However, HTF in this research is synthetic oil Dowtherm™A that has freezing point lower than ambient temperature. Thus, HTF temperature at evaporator outlet is not required. On the other hand, level of working fluid inside evaporator needs to be controlled to prevent emptying and overfilling. Working fluid temperature at condenser outlet is controlled to maintain working fluid at liquid state and reduce temperature variation inside working fluid storage. Thus, working fluid temperature at condenser outlet is assumed to be constant to reduce disturbance in ORC.

As mentioned before, it is difficult to control variables such as HTF temperature at CSP outlet to maximize CSP efficiency in a large solar field. Generally, HTF flow rate at CSP inlet is controlled at set point calculated from optimization. However, process in this research is small-scale CSP. It is possible to control operating temperature of CSP to reduce heat loss. To study dynamic behavior and compare performance of process that use difference controlled variable, process with two tank TES and packed bed TES are simulated using different controlled variable in CSP system. The conventional control strategy used HTF flow rate at CSP inlet as an controlled variable while the proposed control strategy used CSP temperature as controlled variable. Figure 13 and 14 shows controlled variables in process with two tank TES that use conventional control strategy and proposed control strategy, respectively. Table 5.1 and 5.2 show controlled variables of process with two tank TES that use different control strategy.

Table 5.1 Controlled variable of process with two tank TES that use conventional control strategy

Units	Controlled variables
Solar trough	HTF flow rate
Evaporator	Pressure
Evaporator	Level (no steady-state effect)
Expander	Speed
Working fluid storage	Temperature (assume constant)

Table 5.2 Controlled variables of process with two tank that use proposed control strategy

Units	Controlled variables
Solar trough	Temperature
Evaporator	Pressure
Evaporator	Level (no steady-state effect)
Expander	Speed
Working fluid storage	Temperature (assume constant)

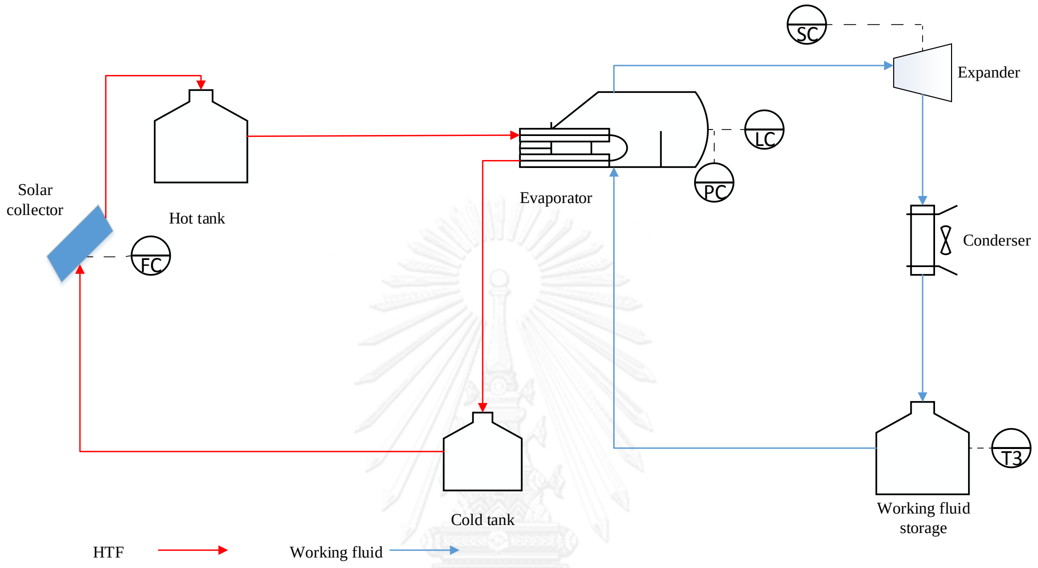

Figure 13. Controlled variables of process with two tank TES that use conventional control strategy

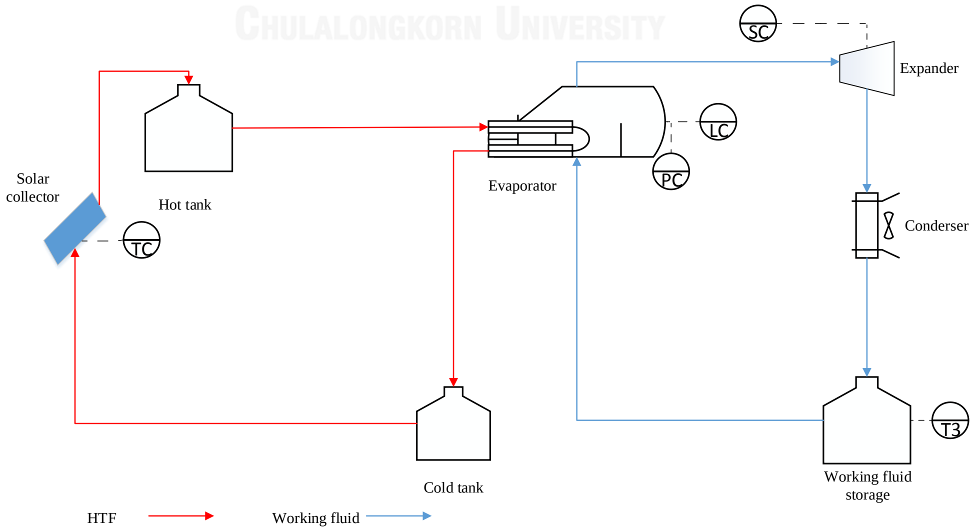

Figure 14. Controlled variables of process with two tank TES that use proposed control strategy

In case of packed bed TES, the system requires three-way valves to switch between 2 modes: charging and discharging. However, large-scale switch mode require experience operator which is not suitable for residential uses. Beside, three-way valve model is not provided in dynamic simulator Dynsim. Control structure of the process with packed bed TES has to be modified. A modified packed bed thermal energy storage is illustrated in Figure 15. The system acts as both thermal energy storage and heat exchanger. Thermal energy from HTF is stored in solid bed inside multiple tubes while transfer thermal energy to working fluid. Solid bed is divided into 5 segments to observe temperature profile. The addition of evaporator is to avoid liquid entering an expander. Process with packed bed TES is shown in Figure 16.

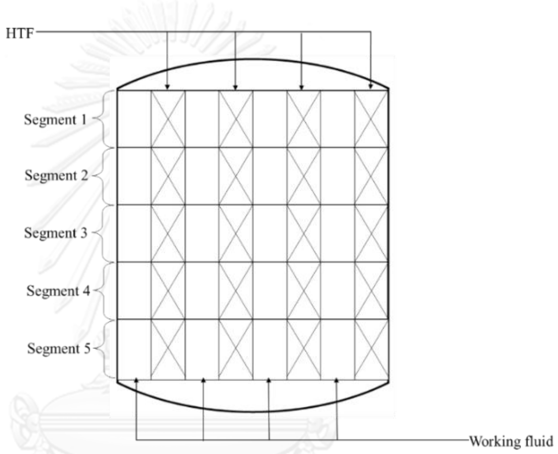

Figure 15. Modified packed bed thermal energy storage

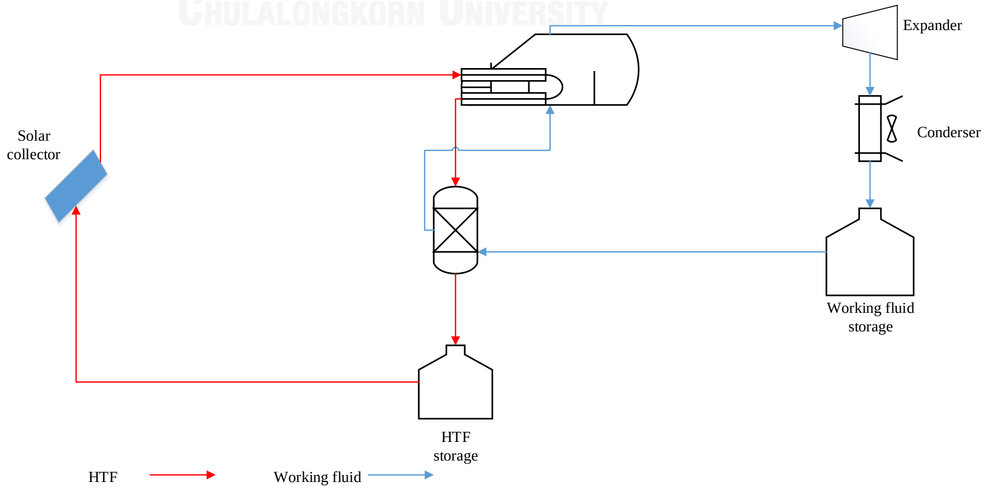

Figure 16. Overall process with packed bed TES

In process with packed bed TES, ORC has the most influence in power generation as it is power conversion system. An expander speed needs to be controlled to satisfy power demand. The efficiency of ORC is defined by enthalpy across expander. Thus, pressure of evaporator needs to be controlled to keep the operating condition constant. Figure 17 and 18 show controlled variable for process with packed bed TES that use conventional control strategy and proposed control strategy, respectively.

However, the proposed control strategy operates based on steady-state optimization which is not include TES. The proposed control strategy control temperature of CSP to minimize heat loss. This control strategy fits well with two tank TES which yield 100% efficiency when heat loss through wall is neglected. Consider equation (8) to (12), efficiency of TES is depend on specific enthalpy of HTF across TES. Thus, temperature across packed bed TES is controlled to maximize TES efficiency. For simplicity, the proposed control strategy that control CSP temperature at certain set point is labeled as control strategy 1. Another proposed control strategy that control temperature difference across packed bed TES is labeled as control strategy 2.

Figure 18 shows controlled variables for process with packed bed TES that use control strategy 1. CSP temperature needs to be controlled to reduce heat loss. Evaporator pressure needs to be control to maintain working fluid enthalpy. Working fluid temperature needs to be controlled to condense working fluid into liquid. An expander speed needs to be controlled to produce power according to power demand. Table 5.3 shows controlled variable of process with packed bed TES that use control strategy 1.

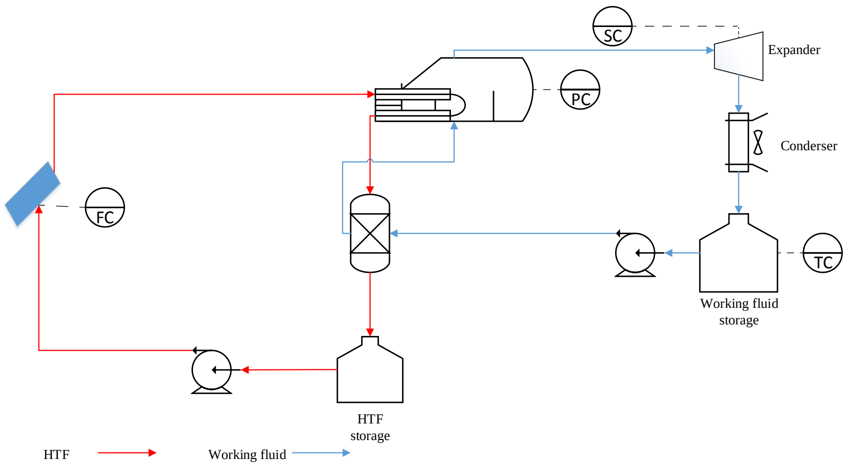

Figure 17. Controlled variables of process with packed bed TES that use conventional control strategy

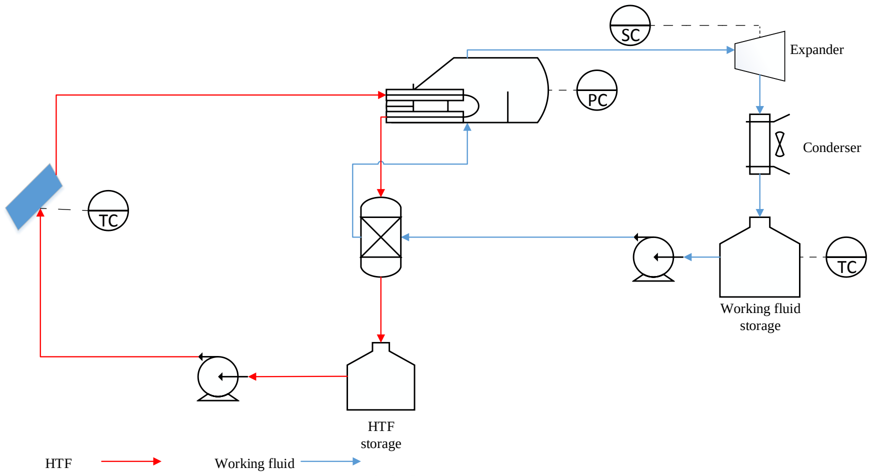

Figure 18. Controlled variables of process with packed bed TES that use control strategy 1

Figure 19 shows controlled variables process with packed bed TES that use control strategy 2. Controlled variable in this strategy is similar to the previous ones with 1 exception, temperature difference between packed bed TES inlet and outlet dT1 needs to be controlled instead of CSP temperature itself to maximize heat transfer between solid bed and HTF. Table 5.4 shows controlled variables of process with packed bed TES that use control strategy 2.

Table 5.3 Controlled variables of process with packed bed TES that use control strategy 1

Units	Controlled variables
Solar trough	Temperature
Evaporator	Pressure
Expander	Speed
Working fluid storage	Temperature (assume constant)

Table 5.4 Controlled variables of process with packed bed TES that use control strategy 2

Units	Controlled variables
Packed bed TES	Temperature difference
Evaporator	Pressure
Expander	Speed
Working fluid storage	Temperature (assume constant)

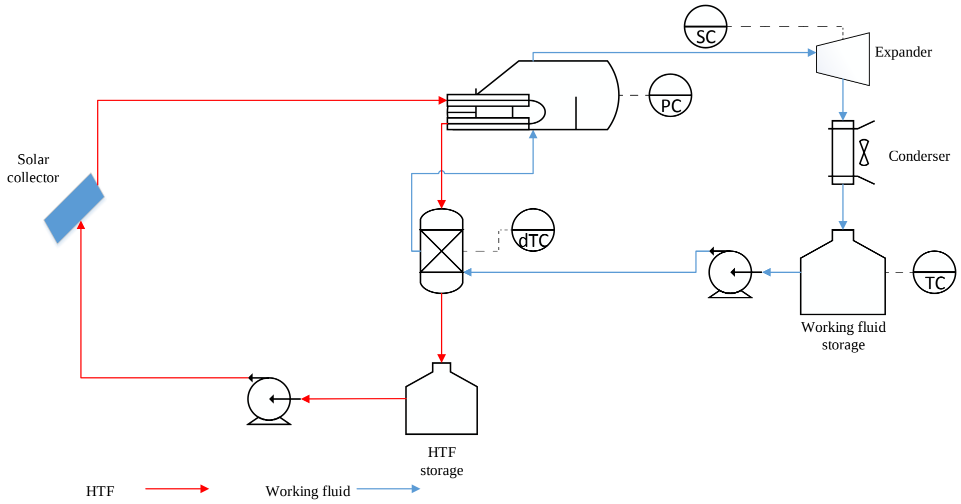

Figure 19. Controlled variables of process with packed bed TES that use control strategy 2

b.) Manipulated variable: A good manipulated variable should have large effect on output and a small effect on controlled variables controlled by other manipulated variable.

Consider the overall process with two tank TES in Figure 14, the process consists of 3 tanks, 1 evaporator (kettle type boiler), 1 expander and 1 condenser. Controlled variables in this process can be controlled by manipulate hot and cold stream. Control valve V1, V2, V3 and V4 are used to manipulate fluid from cold tank, hot tank, working fluid storage and evaporator, respectively. Since the stream at expander inlet is given by evaporator while outlet is depended on power demand, there is no manipulated variable for expander. Normally, air stream is manipulated variable for air condenser to adjust the level of sub-cooling. However, working fluid leaving condenser is assumed to be constant to reduce disturbance in ORC. Thus, there is no manipulated variable for condenser. The control valves of process with two tank TES is shown in Figure 18. List of manipulated variable is shown in Table 5.5

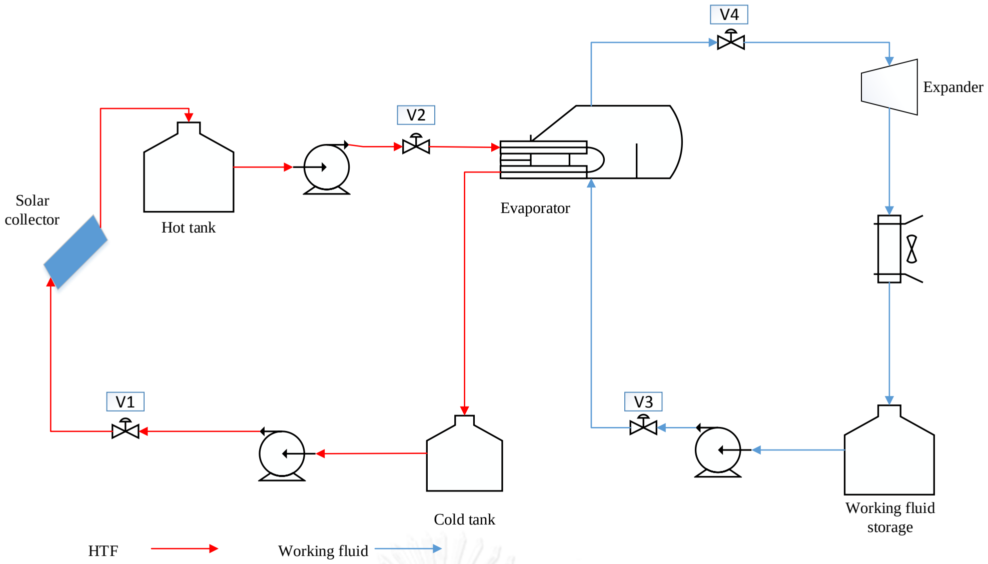

Figure 20. Control valve for process with two tank TES

Table 5.5 Manipulated variables and associated valve for two tank TES

Manipulated variables	Valve
Hot tank flow rate	V1
Cold tank flow rate	V2
Working fluid storage flow rate	V3
Expander inlet flow rate	V4

In case of process with packed bed TES, the number of manipulated variables is 1 less than that of process with two tank TES because there is only 1 HTF storage. Although there are 2 different control strategies for process with packed bed TES, the equipment is still the same. Thus, manipulated variables of process with packed bed TES using different control strategy is the same. Control valve V1, V2 and V3 are used to manipulate fluid stream from HTF storage, working fluid storage and evaporator, respectively. The control valve V4 is added at evaporator inlet to start-up/shut-down ORC system. Control valves for process with packed bed TES is shown in Figure 21. List of manipulated variable in process with packed bed TES that use control strategy 1 is shown in Table 5.6

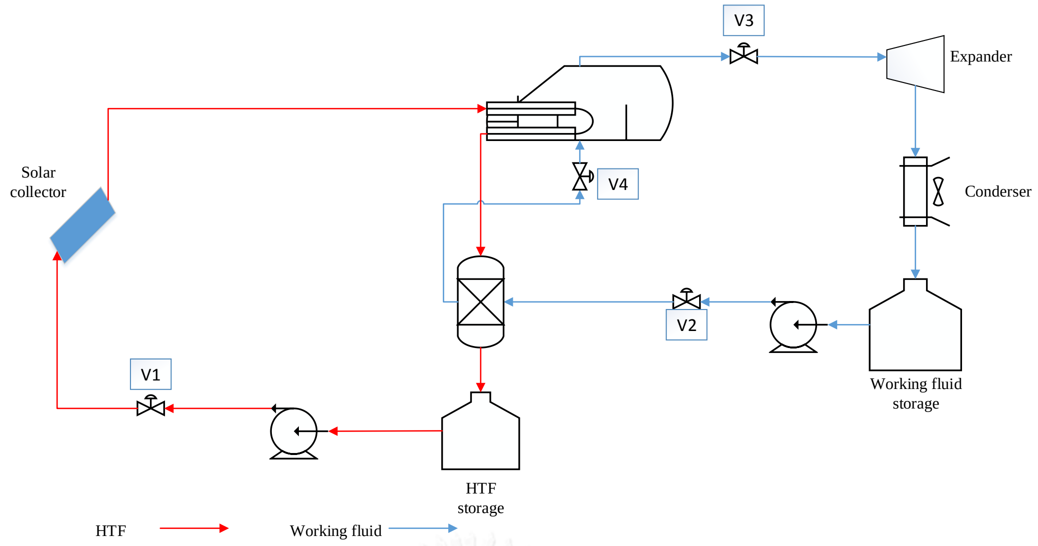

Figure 21. Control valves for process with packed bed TES

Table 5.6 Manipulated variables and associated valve for packed bed TES

Manipulated variables	Valve
HTF storage flow rate	V1
Working fluid storage flow rate	V2
Expander inlet flow rate	V3
Evaporator inlet flow rate	V4

c.) Degree of freedom: Degree of freedom is the number of variable that must be specified in order to control the process. Concept to identify degree of freedom is subtracting the number of variables with the number of equation related to the process. However, in a large process, it is easy to miscalculate the number. Thus, the number that is calculated in this research is steady-state controlled variables or steady-state degree of freedom N_{ss}. Steady-state degree of freedom is the number of variable that can be controlled in the process and is used for optimization. If the steady-state degree of freedom is less than controlled variables, additional manipulated variables might be necessary. The number of steady-state degree of freedom can be determined by counting manipulated variables and subtracting by number degree of freedom with no steady-state effect N_0.

$$N_{ss} = N_{MV} - N_0 \tag{16}$$

According to manipulated variables section, process with two tank TES has number of manipulated variables N_{MV} = 4. An evaporator acts as liquid receiver with liquid level controller to avoid evaporator from dry out or overflow. Although liquid level inside evaporator is one of the manipulated variable, it has no steady-state effect. Thus, the process has number of non-steady-state variables $N_0 = 1$. In conclusion, the process with two tank TES has Steady-state degree of freedom $N_{ss} = 3$.

In case of process with packed bed TES, the process has number of manipulated variables $N_{MV} = 3$ (excluding V4 that is added for start-up/shut-down purpose). Since there is no variable that has no steady-state effect $N_0 = 0$, steady-state degree of freedom of process with packed bed TES $N_{ss} = 3$.

Although process with packed bed TES with different control strategy has the same manipulated variables, controlled variables are different. For process with packed bed TES that control strategy 1, the steady-state degree of freedom $N_{ss} = 3$ includes CSP temperature, expander speed and evaporator pressure.

In case of process with packed bed TES that use control strategy 2, temperature difference between packed bed TES inlet and outlet is focused on rather than temperature of CSP. The steady-state degree of freedom $N_{ss} = 3$ includes temperature difference between packed bed TES inlet and outlet, expander speed and evaporator pressure.

5.2.3 Step 3: Select primary controlled variable

Primary controlled variable is a variable that must be controlled in order to make the process operates according to operational objective (maximum overall efficiency). It should be easily measured and sensitive to changes of manipulated variable. The set point of primary controlled variable link control layer with optimization layer. Since, objective of this chapter is to design and propose new control strategy, conventional control strategy will not be discussed any further.

In this process, the objective function (steady-state overall efficiency) is greatly depended on efficiency of CSP and ORC. The efficiency of CSP does not only depend on equipment specification but operating temperature as well. The higher operating temperature results in more heat loss from receiver tube of parabolic trough. Thus, temperature of CSP outlet should be controlled variable. In case of ORC efficiency, the temperature and pressure of working fluid define enthalpy at expander entrance which should be kept at optimal condition. Generally, quantitative approach should be calculated for input-output pairing. However, as illustrated in Figure 18, it is obvious that each primary controlled variable only has 1 manipulated variable. There is only HTF flow rate at cold tank outlet that can be used to control temperature of HTF at CSP outlet while HTF flow rate at hot tank is the only manipulated variable that can control expander inlet pressure. Table 5.7 shows the input-out pairing for primary variables for process with two tank TES

Table 5.7 Primary controlled variables and manipulated variables for process with two tank TES

Primary controlled variables	Manipulated variables
CSP outlet temperature	cold tank outlet flow rate
Expander inlet pressure	hot tank outlet flow rate

In case of pack bed, there are 2 different control strategies. For process with packed bed TES that use control strategy 1, primary controlled variables are also CSP outlet temperature and expander inlet pressure. As illustrated in Figure 17, each primary controlled variable has 1 manipulated variable. There is no manipulated variable to control the temperature at CSP outlet except HTF flow rate at HTF storage outlet. As for the pressure inside evaporator, the only suitable manipulated variable is working fluid flow rate at working fluid storage outlet. Table 5.8 shows the input-output pairing for primary variables for process with packed bed TES that use control strategy 1.

For process with packed bed TES that use control strategy 2, primary controlled variable become expander inlet pressure and temperature difference between TES inlet and outlet. Each primary controlled variable still has only 1 potential manipulated variable: working fluid storage outlet flow rate is used to control evaporator pressure while HTF storage outlet flow rate is used to control temperature difference between packed bed at inlet and outlet. Table 5.9 shows the input-output pairing for primary variables for process with packed bed TES that use control strategy 2.

Table 5.8 Primary controlled variables and manipulated variables for process with packed bed TES that use control strategy 1

Primary controlled variables	Manipulated variables
CSP outlet temperature	HTF storage outlet flow rate
Expander inlet pressure	Working fluid storage outlet flow rate

Table 5.9 Primary controlled variables and manipulated variables for process with packed bed TES that use control strategy 2

Primary controlled variables	Manipulated variables
Temperature difference between TES inlet and outlet	HTF storage outlet flow rate
Expander inlet pressure	Working fluid storage outlet flow rate

5.2.4 Step 4: Where should production rate be set?

The purpose of this step is to decide which controller should be throughput manipulator (TPM). TPM is the manipulator that control the production rate of the process. It is very important to select a proper controller to be TPM as it determine the structure of remaining control system. Commonly, TPM set point is held constant to maintain stable operation. However, the power demand in household is not constant. The controller that should be TPM is a controller that power output sensitive to the most. The variable that has the fastest effect on power output is working fluid flow rate at expander entrance as it affect the enthalpy in and out of the expander. Thus, the valve at expander entrance is selected as TPM.

5.2.5 Step 5: Regulatory control layer

Regulatory control layer is the first step of bottom-up part in control structure design. The main issue in regulatory control layer is not only to decide how to deal with disturbances and unsafe operating condition, but secondary variable selection as well. Secondary variable is a variable that which kept at set point results in optimal primary variable value. After primary variable set point is calculated from optimization layer to implement in supervisory control, supervisory control calculate secondary variable set point for regulatory control to adjust valves accordingly. Block diagram of process control hierarchy is illustrated in Figure 22.

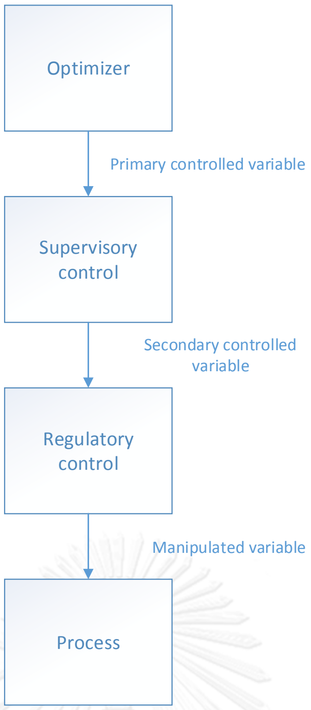

Figure 22. Block diagram of process control hierarchy

a.) Secondary variables: Generally, control layers is separated into 2 layers, fast regulatory control and slow supervisory control. However, the process in this research apply PI controller which is consider very fast control. Thus, secondary variable selection is no longer needed.

b.) How to handle disturbance: The disturbance in process with two tank TES and packed bed TES is solar irradiance. Solar irradiance is heat power input of the system and affects CSP performance directly. However, this problem is handled by using temperature control to control HTF temperature at CSP outlet in step 3.

c.) How to handle unsafe operating condition: In process with two tank TES, a potential variable that pose a threat toward process safety is level of working fluid inside boiler. The working fluid level must be controlled at above the height of heating coil. Besides, it also prevent boiler from being dry out. The most variable that has most effect to working fluid level is working fluid flow rate at boiler entrance which is regulated by valve V2. List of potential controlled variable is shown in Table 5.10. The control structure of process with two tank TES is illustrated in Figure 23.

In case of pack bed TES, the process produce power by using working fluid to gather thermal energy from solid bed. The more thermal energy the process consume, the lower temperature difference between solid bed and working fluid. The process can operates until the temperature of packed bed is too low to evaporate working fluid. Thus, it has to be shut down. Generally, ORC can be shut down by simply manually close valve V2. However, this process is designed for residential application which should be operates automatically. Thus, working fluid flow rate at boiler entrance should be controlled by valve V3 for start-up and shut-down ORC when temperature difference between solid bed segment and working fluid is too low.

Another unsafe operating condition may occur when there is too much solar irradiance for solid bed to collect. This probably happen with the process that use maximum temperature difference across TES as control strategy. As the solid bed collect thermal energy, temperature of difference across TES increase until it hit upper constraint such as maximum temperature that expander can handle which in this case is 175 °C. Thus, CSP need to be shut down. Unfortunately, the process does not have another manipulated variable to deal with this problem. The override control need to take control of the process and shut down CSP until expander inlet drop below maximum temperature for expander. List of potential controlled variable is shown in Table 5.11 and 5.12.The final control structure of process with packed bed TES is illustrated in Figure 24.

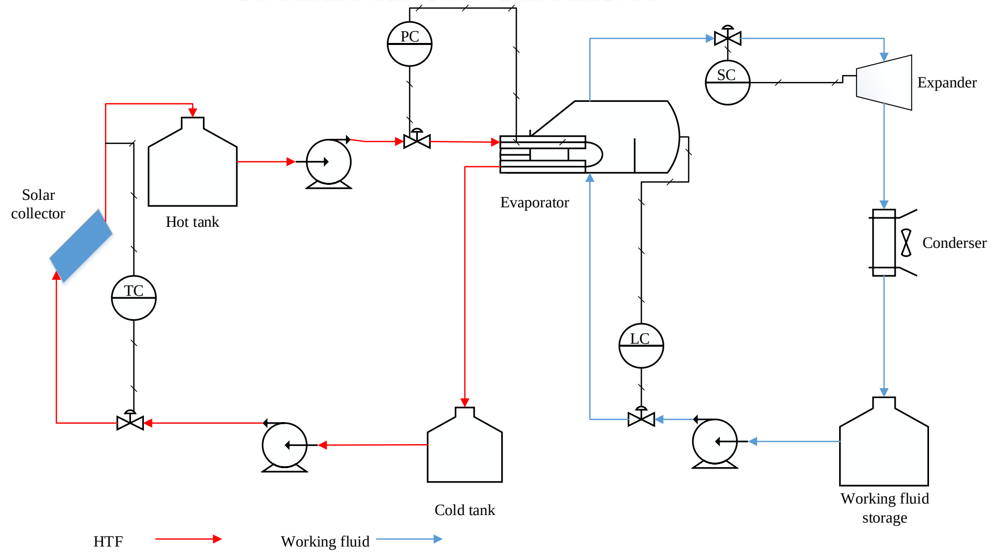

Figure 23. Overall control structure of process with two tank TES

Table 5.10 Potential controlled variable for process with two tank TES that use proposed control strategy

Controlled variable	Manipulated variable
CSP outlet temperature (primary)	Cold tank outlet flow rate
Expander pressure (primary)	Hot tank outlet flow rate
Evaporator level	Working fluid storage outlet flow rate
Expander inlet flow rate (TPM)	Expander inlet flow rate

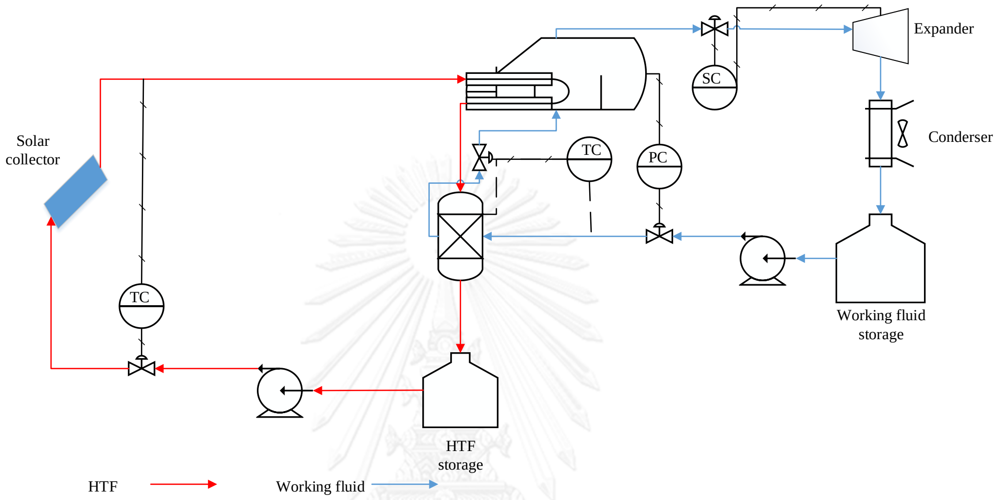

Figure 24. Overall control structure of process with packed bed TES that use control strategy 1

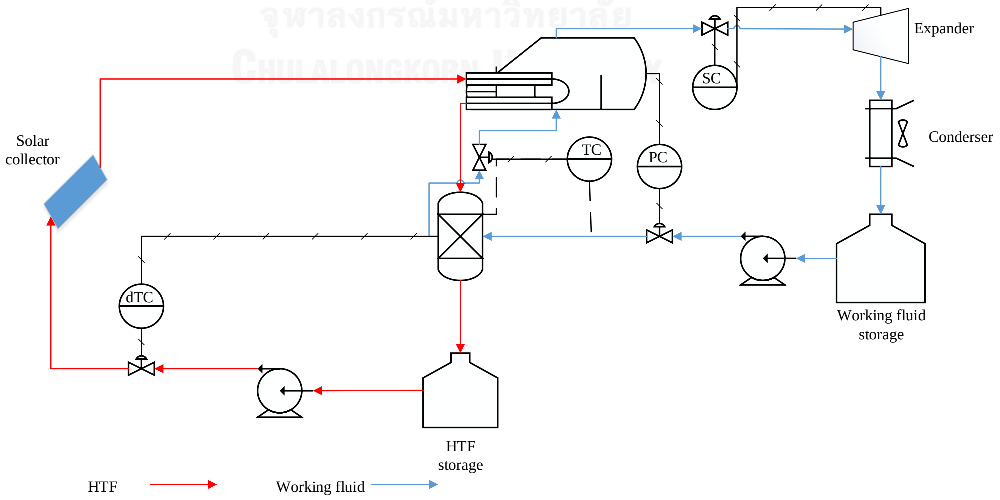

Figure 25. Overall control structure of process with packed bed TES that use control strategy 2

Table 5.11 Potential controlled variable for process with packed bed TES that use control strategy 1

Controlled variable	Manipulated variable
CSP outlet temperature (primary)	HTF storage outlet flow rate
Expander pressure (primary)	Working fluid storage outlet flow rate
Temperature difference between solid bed and working fluid	Working fluid flow rate at evaporator inlet
Expander inlet flow rate (TPM)	Expander inlet flow rate

Table 5.12 Potential controlled variable for process with packed bed TES that use control strategy 2

Controlled variable	Manipulated variable
Temperature difference between TES inlet and outlet (primary)	HTF storage outlet flow rate
Expander pressure (primary)	Working fluid storage outlet flow rate
Temperature difference between solid bed and working fluid	Working fluid flow rate at evaporator inlet
Expander inlet flow rate (TPM)	Expander inlet flow rate

Step 6 and 7 focus on more advanced control and real-time optimization which is not mentioned in this study.

5.3 Control system

The control system is added to dynamic simulation according to the design of control structure from previous chapter. This dynamic simulator program provides PID controller for user to control the process. This research apply SIMC tuning method to determine controller gain and integral time of PI controller and will be discussed as follow.

SIMC tuning method is a method to calculate controller gain and integral time based on step response. Process parameter can be estimated from the response of the system to a step change in controller output. The controller is set to manual mode until the system become steady. Then, the manipulated variable is change. The response of the process can be used to determine three process parameters: gain, time constant and delay time. Figure 21. shows an open-loop step response in step response experiment.

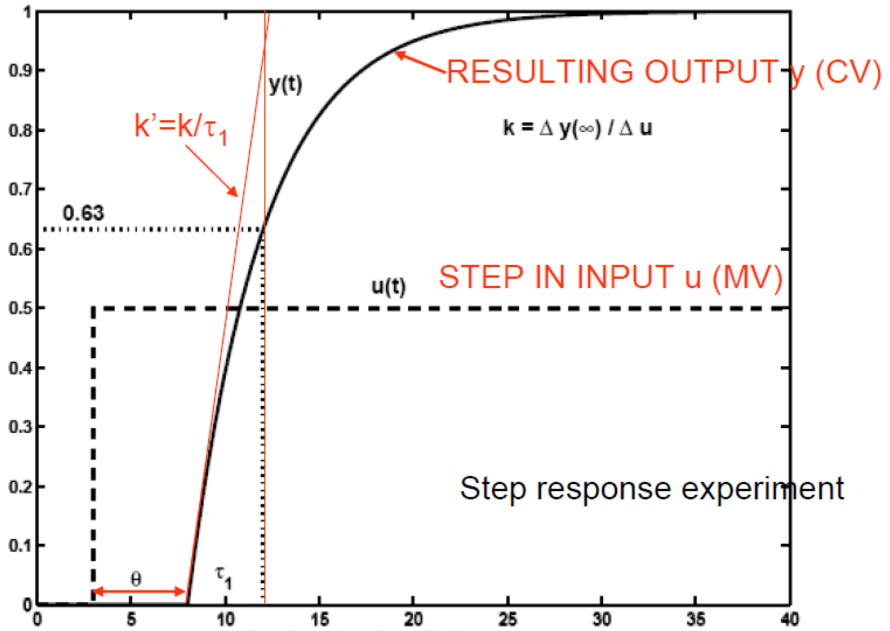

Figure 26. Open-loop step response to determine process parameters

Where θ is delay time

τ_1 is time constant (additional time of 63% to reach final value)

k is steady-state gain

k' is slope after response take off

With SIMC tuning method, controller gain and integral time can be determined by equation (21) and (22).

$$K_c = \frac{1}{k'} \times \frac{1}{\theta + \tau_c} \tag{21}$$

$$\tau_I = \min(\tau_1, 4(\tau_c + \theta)) \tag{22}$$

The advantage of this tuning method is that it can adjust the tightness of control for either fast or smooth response by changing desired closed-loop response time τ_c. Increasing τ_c results in smoother response.

5.4 Dynamic simulation

Dynamic simulation is an effective tools to study the process behavior. It is able to simulate process in different aspect that steady-state simulation cannot do such as the start-up and shut-down process or the level of fluid in tanks. The dynamic simulator used in this research is Dynsim because it cooperates well with the steady-state simulator PRO/II. There are many interesting issue that will be mentioned in this section including design of the process, study process behavior and tuning method for controller.

5.4.1 Design of process

Unlike steady-state simulation, the dynamic simulation is able to simulate the dynamic behavior of TES. Thus, the process for dynamic simulation is the combination of 3 systems: CSP, TES and ORC.

One of the benefit of dynamic simulator Dynsim is that it cooperates with the steady-state simulator PRO/II. By using function “Send to Dynsim”, the dynamic simulation will be generated based on the equipment and specification of the steady-state simulation. However, some equipment such as tank, pipe and drum are not included in steady-state simulation and have to be added into dynamic simulation.

Solar collector of CSP is represented by pipe model in dynamic simulation. It is modeled after the commercial solar trough unit shown in Table 3.1. Since tube inner diameter and thickness is constant throughout CSP, length of the pipe indicates the area of solar field which is defined by steady-state simulation. The thermal energy from the sun is directly transfer to HTF inside receiver tube by input the “Imposed heat to fluid” in pipe model specification. The imposed heat to fluid does not have to be a constant value. A standalone point is added for user to input solar irradiance at specific time. Then, add miscellaneous equation model to specify the imposed heat to fluid of the pipe. Solar irradiance is not only variable that is input directly by using miscellaneous equation model. Heat loss $\dot{Q}_{loss}$ in equation (5) is also defined by using miscellaneous equation model and connect it to “Heat loss from metal to ambient” of pipe model.

Another model that is not included in steady-state simulation is tank. The most important specification of tank is its volume. Tank volume is determined from HTF volumetric flow rate from steady-state simulation with maximum mean value of solar irradiance.

There are other equipment that difficult to model individually in dynamic simulation but they can be modeled by integrating to other model. Boiler which is easily model by simple heat exchanger in steady-state simulation is modeled by 2 different models, utility exchanger and drum. There are 5 options for utility exchanger: water, air, other fluids, constant metal temperature and heat stream. To modeled boiler, heat stream option is selected. Then, connect utility exchanger and drum with heat stream (pink line). The specification of utility exchanger can be obtain by convert simple heat exchanger from steady-state simulation. Boiler model is illustrated in Figure 27.

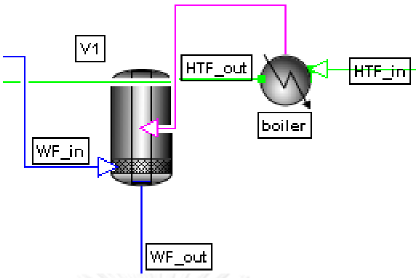

Figure 27. Boiler model in dynamic simulation

Expander model is also difficult to model. The model need to be attached with shaft model by mechanical stream in order to observe expander speed. For accuracy in dynamic simulation, performance of expander is modeled after performance graph of commercial expander. The polynomial function is generated from power-RPM graph and input to friction loss of shaft. The expander efficiency which is a function of expander speed is input to expander as reference expander efficiency. To manipulated working fluid flow rate at expander entrance, a graphical valve is added to expander to adjust flow conductance. Expander model is shown in Figure 28.

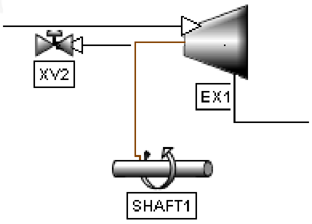

Figure 28. Expander model attached with shaft model and graphical valve

5.2.1.1 Two tank thermal energy storage

Normally, the temperature of HTF in hot tank is kept constant to reject the disturbance (solar irradiance) from CSP. The dynamic behavior of two tank TES can be explained by mass balance in equation (15).

$$A\frac{dh}{dt}=q_{in}-q_{out} \tag{15}$$

Where A is cross section area of cylindrical tank, q is level of HTF and q is volumetric flow rate in and out of the tank. Thus, tanks volume is designed from volumetric flow rate of HTF from CSP at optimal temperature. Figure 29 illustrate the dynamic simulation with two tank TES.

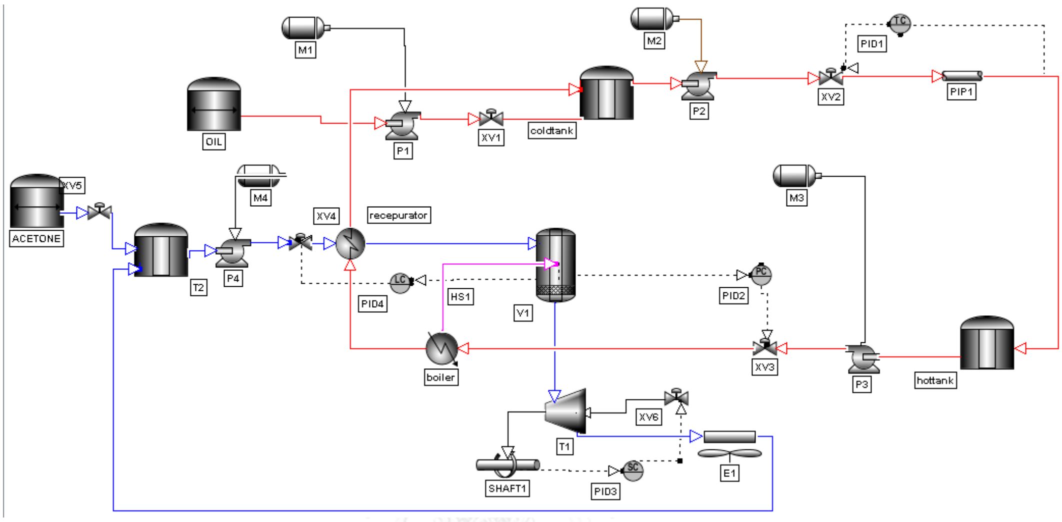

Figure 29. Dynamic simulation with two tank TES

5.2.1.2 Pack bed thermal energy storage

The energy in packed bed TES is represented by temperature of solid and working fluid of inside TES. The volume packed bed TES can be defined by using equation (17).

$$V=\frac{E_{\max}}{(\rho_b c_b(1-\varepsilon)+\bar{\rho}_f\bar{c}_f\varepsilon)\Delta T_{\max}} \tag{17}$$

Where $E_{\max}$ is maximum stored energy, ρ is density, C is specific heat capacity and ε is bed void fraction. The subscripts b and f stand for bed and fluid, respectively. The parameter of solid is shown in Table 5.13.

Table 5.13 Parameter of solid bed

	Value	Unit
Component	alumina (Al_2O_3)	
Density	3550	kg/m3
specific heat	920	J/kg °C
Bed void fraction	0.4	
Particle diameter	10	mm

Convective heat transfer coefficient between HTF and solid bed, α, is determined by equation (18) to (21).

$$\alpha = \frac{Nuk}{d} \tag{18}$$

$$Nu = 2 + 1.1(\mathrm{Re}^{0.6}\,\mathrm{Pr}^{0.33}) \tag{19}$$

$$\mathrm{Re} = \frac{D_{particle} V_s \rho_b}{(1-\varepsilon)\mu} \tag{20}$$

$$\mathrm{Pr} = \frac{C_f \mu}{k_f} \tag{21}$$

Where α is convective heat transfer coefficient, Nu is Nusselt number, Re is Reynolds number and Pr is Prandtl number. Reynolds number is obtained by using PFR model in steady-state simulation for superficial velocity. Process with packed bed TES is illustrated in Figure 30.

The model that suitable for packed bed TES is plug flow reactor (PFR). The number of flow pass and reaction can be input freely. In this case, configuration for packed bed TES is PFR with 2 walls, 1 flow pass, 1compressible pass and 5 hold ups per wall. Heat loss from TES to ambient is neglected.

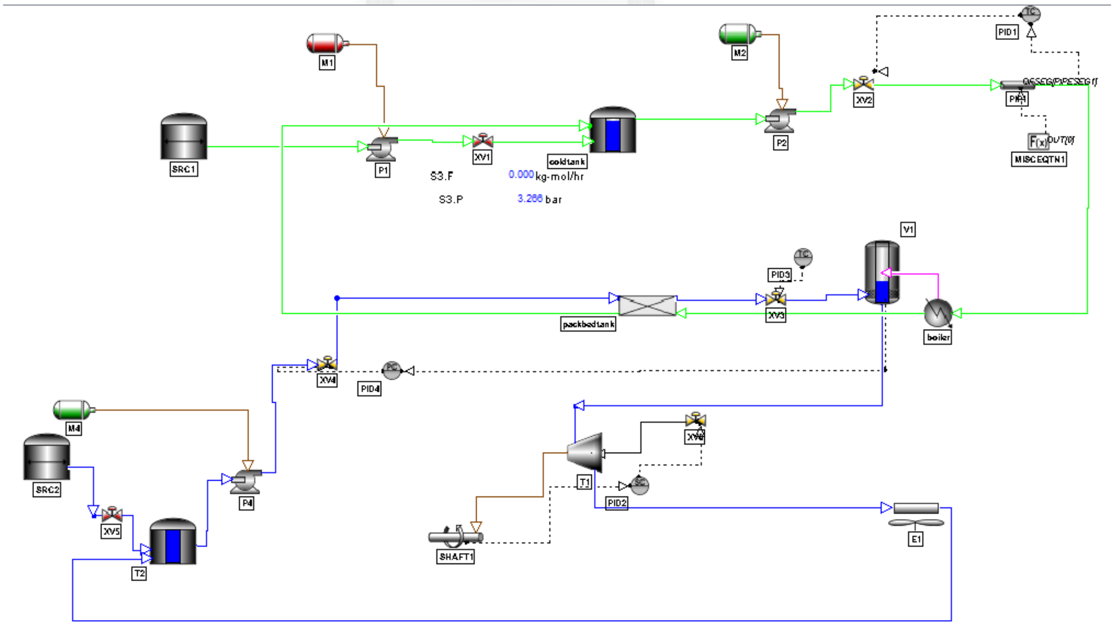

Figure 30. Overall process with packed bed TES

5.4.2 Simulation scenario

In this research, Dynamic simulation is designed based on steady-state simulation. The operating conditions are obtained by assumption of constant solar irradiance. However, solar irradiance in real plant is not constant. The process must undergo disturbance from solar irradiance. Therefore, an actual solar irradiance is applied in dynamic simulations. Data of solar irradiance is taken in Bangkok in 2009. Dynamic simulation is operate for 48 hours.

The process in this research focus on power production from small-scale CSP to satisfy power demand at certain set point which is different from conventional solar power plant. The control strategy of conventional solar power plant is adapted in this research and compared to proposed control strategy.

There are 2 proposed control strategies for process with packed bed TES. The first process operates at the same operating condition as the process with two tank TES (control strategy 1). Another control strategy is to control maximum temperature difference across packed bed TES to increase heat transfer between HTF and solid bed (control strategy 2). The result of both control strategies will be compare and discussed in next chapter.

Chapter 6
Result and discussion

6.1 Steady-state simulation results

The objective of steady-state simulation in this research is to determine the optimal operating condition and sizing of process equipment. The optimizer model provided by the steady-state simulator program PRO/II was used to determine the optimal operating condition with steady solar irradiance. The mean value of solar irradiance was applied as heat duty for sizing equipment purposes.

6.1.1 Results of steady-state optimization

From previous chapter, ORC system is simulated in steady-state simulator to determine the optimal operating condition to maximize the objective function, overall steady efficiency, by determine minimum CSP temperature to minimize CSP heat loss. Working fluid flow rate and pressure are varied while heat duty from CSP, outlet expander pressure and range of power production are constraints. Result is shown in Table 6.1.

Table 6.1 Results of ORC steady-state optimization TES

	Value	Unit
Stream WF1		
Flow rate Pressure	1.132	kg-mol/°C
Stream WF5		
Pressure	3.5	bar
Heat exchanger BOLIER1		
Duty	38.3	MJ/hr

From the optimization, the thermal efficiency is 7.05%. The minimum solar field area is around 75 m^2 with 14 units of commercial parabolic trough CSP. By using equation (4), the minimum heat input for CSP becomes 121 MJ/hr.

After operating condition of ORC is defined, CSP is integrated to ORC to define the optimal operating condition of CSP when both systems are working together. As illustrated in Figure 9, the optimizer is added to minimize HTF enthalpy at CSP inlet for minimum heat loss. However, temperature cross over occurs between heat exchanger and boiler. The constraint of optimizer is added to prevent this problem by specified the ratio of HTF8 temperature and WF4 temperature to be more than 1. The optimal operating condition of CSP-ORC steady-state simulation for process with two tank TES is shown in Table 6.2.

Table 6.2 Results of CSP-ORC steady-state optimization for process with two tank TES

	Value	Unit
Stream HTF1		
Flow rate Temperature	7 85	kg-mol/hr °C
Stream HTF4		
Temperature	150	°C

However, there are 2 control strategies for process with packed bed TES. Another control strategy for packed bed TES is to control temperature difference across packed bed TES. The results of CSP-ORC steady-state optimization from process with packed bed TES that use temperature difference across TES as control strategy is shown in table 6.3

Table 6.3 Results of CSP-ORC steady-state optimization for process with packed bed TES that use control strategy 2

	Value	Unit
Stream HTF1		
Flow rate Temperature	5 95	kg-mol/hr °C
Stream HTF4		
Temperature	175	°C

6.2 Dynamic simulation

Dynamic simulation is used to study behavior of process with different TES, process with two tank TES and packed bed TES, and compare their performance.

6.2.1 Design of process

Dynamic simulation is used to study dynamic behavior of process that cannot be simulated in steady-state simulation such as dynamic behavior of TES under disturbance of inconsistency solar irradiance. This section includes comparison between process that used control structure in conventional solar power plant and control structure that is designed using plant wide control. Then, the performance of process with different TES is compared, process with two tank TES and packed bed TES.

6.2.1.1 Process with two tank TES

Cold and hot tank are designed based on volumetric flow rate of HTF at optimal temperature. They have the same dimension: 2 m in diameter and 5 m high ($15.7 m^3$). It is assumed that both tank is well-insulated, so heat loss to ambient can be neglected. The overall process with two tank TES is illustrated in Figure 24. HTF flows from cold tank to hot tank collecting thermal energy from CSP which is modeled by PIP1. The actual solar irradiance in Thailand and heat loss model are added to CSP. The temperature of HTF at CSP exit is controlled by temperature controller PID1 at 150 °C. HTF leave hot tank at constant temperature to heat up working fluid inside boiler. The boiler pressure which is primary controlled variable is controlled by pressure controlled PID2 at 3.5 bar for maximum thermal efficiency. The production rate is controlled by adjusting graphical valve using speed controller PID3. The level of working fluid inside boiler is controlled by level controller at 0.2 m. The controller is tuned by SIMC method. The specification of key equipment and controller are shown in Table 6.4 to 6.6

Table 6.4 Specification of tanks

Tank		
Name	hot tank	cold tank
Diameter (m)	2	2
Length (m)	3	3
Blanket gas pressure (bar)	1	3

Table 6.5 Specification of heat exchanger

Heat exchanger			
Name	boiler	recuperator	E1
Heat transfer area (m^2)	2.4724	0.15	0.86
Mass flow references for heat transfer coefficient (kg/hr) (Process side)	65	65	65
Mass flow references for heat transfer coefficient (kg/hr) (Utility side)	-	305.39	72000
Heat transfer coefficient at reference flow (kW/m^2-K)	0.5	0.5	1.3
Natural convection heat transfer coefficient (kW/m^2-K)	0.001	0.1	0.001

Table 6. 6 Specification of controller

Controller				
Name	PID1	PID2	PID3	PID4
Configuration	Temperature control	Pressure control	Speed control	Level control
Input high limit	300°C	13.8 bar	3600 rpm	0.25 m
Input low limit	0 °C	1 bar	0 rpm	0 m
Proportional gain	0.84	2.5	0.315	2
Integral reset time (s)	311	80	10	100
Derivative time (s)	0	0	0	0
Set point	150 °C	3.5 bar	1935 rpm	0.2 m

In case of the process with two tank TES that control HTF flow rate at CSP inlet, the specification of the process is the same. However, controllers are different because it has different control variable. List of controller in process that used conventional control structure is shown in Table 6.7

Table 6.7 Specification of controller in process with two tank TES that use conventional control structure

Controller				
Name	PID1	PID2	PID3	PID4
Configuration	Flow control	Pressure control	Speed control	Level control
Input high limit	12 kg-mol/hr	13.8 bar	3600 rpm	0.25 m
Input low limit	0 kg-mol/hr	1 bar	0 rpm	0 m
Proportional gain	0.416	2.5	0.315	2
Integral reset time (s)	7.5	80	10	100
Derivative time (s)	0	0	0	0
Set point	7 kg-mol/hr	3.5 bar	1935 rpm	0.2 m

6.2.1.2 Process with packed bed TES

The overall process with packed bed TES is illustrated in Figure 25. There are 2 control strategies to control this process. The first one operates at the same operating conditions as the process with two tank TES. The temperature from CSP is kept at 150 °C. Packed bed TES minimum volume determined by using equation (17) is 11 m^3. However, the safety factor of 2 is applied to ensure that packed bed has enough capacity for thermal energy for whole day. HTF from CSP flows through packed bed TES during the day to charge thermal energy inside solid bed. Then, working fluid flows through

TES to receive thermal energy for power production. The boiler is added to prevent liquid working fluid to enter expander. The valve at boiler entrance control temperature difference between the hottest solid segment and working fluid temperature at TES entrance by using P control PID3.

Another control strategy for packed bed TES is to control maximum temperature difference across packed bed TES. The temperature difference across the TES is kept at 80°C (maximum expander specification temperature). The specification of key equipment and controller are shown in table 6.8 to 6.11

Table 6.8 Specification of packed bed TES

Packed bed tank	
Name	packbedtank
Reactor length (m)	10
Reactor inside diameter (mm)	1708
Compressible wall area (m^2)	220
Force convection heat transfer coefficient between HTF and solid bed (kW/m^2-K)	0.105

Table 6.9 Specification of heat exchanger

Heat exchanger	
Name	boiler
Heat transfer area (m^2)	0.25
Mass flow references for heat transfer coefficient (kg/hr) (Process side)	771
Mass flow references for heat transfer coefficient (kg/hr) (Utility side)	-
Heat transfer coefficient at reference flow (kW/m^2-K)	0.5
Natural convection heat transfer coefficient (kW/m^2-K)	0.001

Table 6.10 Specification of controller of process with packed bed that use control strategy 1

Controller				
Name	PID1	PID2	PID3	PID4
Configuration	Temperature control	Pressure control	Speed control	Temperature difference control
Input high limit	300°C	13.8 bar	3600 rpm	0.5 m
Input low limit	0 °C	1 bar	0 rpm	0 m
Proportional gain	0.84	1.1	0.315	5
Integral reset time (s)	311	70	10	100
Derivative time (s)	0	0	0	0
Set point	150 °C	3.5 bar	1935 rpm	80 °C

Table 6.11 Specification of controller of process with packed bed that use control strategy 2

Controller				
Name	PID1	PID2	PID3	PID4
Configuration	Temperature control	Pressure control	Speed control	Temperature difference control
Input high limit	300°C	13.8 bar	3600 rpm	0.5 m
Input low limit	0 °C	1 bar	0 rpm	0 m
Proportional gain	1.31	1.1	0.315	5
Integral reset time (s)	525	70	10	100
Derivative time (s)	0	0	0	0
Set point	80 °C	3.5 bar	1935 rpm	80 °C

In case of process that used control structure from conventional solar power plant, the specification of equipment is the same. This process control HTF flow rate at CSP inlet instead of temperature of CSP. The specification of controller in process with packed bed TES that used control structure from conventional solar power plant is shown in Table 6.12

Table 6.12 Specification of controllers in process with packed bed TES that use conventional control structure

Controller				
Name	PID1	PID2	PID3	PID4
Configuration	Flow control	Pressure control	Speed control	Temperature difference control
Input high limit	12 kg-mol/hr	13.8 bar	3600 rpm	0.5 m
Input low limit	0 kg-mol/hr	1 bar	0 rpm	0 m
Proportional gain	0.416	1.1	0.315	5
Integral reset time (s)	7.5	70	10	100
Derivative time (s)	0	0	0	0
Set point	7	3.5 bar	1935 rpm	80 °C

6.2.1.3 Solar irradiance

The dynamic simulation of both process operates for 48 hours. The start-up and shut-down of process operate automatically. The solar irradiance is input to pipe model as imposed heat to fluid with heat loss from equation (2). Figure 31 shows solar irradiance in Thailand.

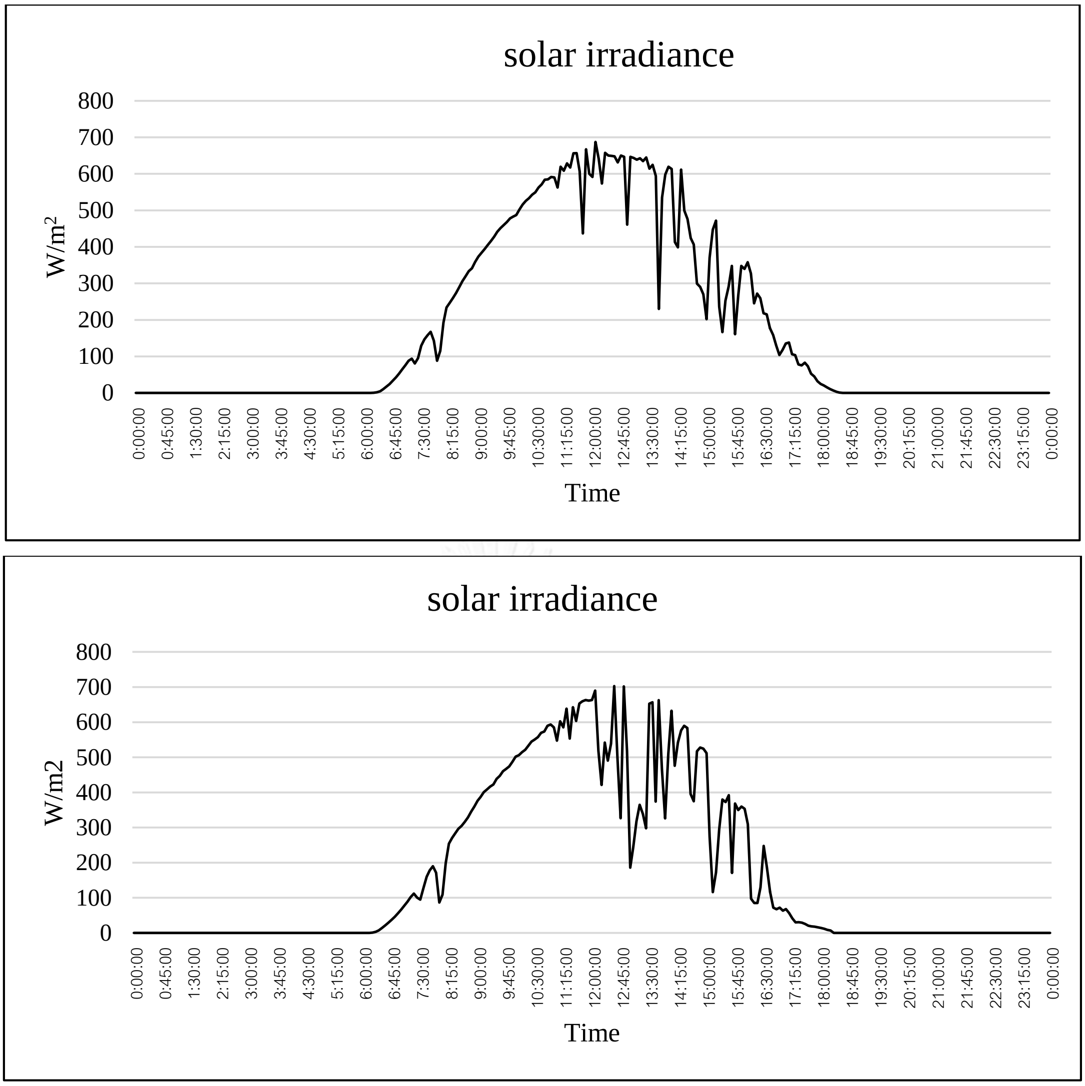

Figure 31. Solar irradiance

6.2.2 Control structure comparison

To study the effect of controlled variable of CSP, the process behavior and performance of CSP that use conventional control structure and CSP that has CSP temperature as controlled variable are study and compared. Figure 32 shows 24-hour power production of process with two tank TES that controlled by different control variable at expander shaft speed 1935 RPM (power 750 W). Both processes can produce stable power with unstable solar irradiance for entire day. The effect of disturbance from solar irradiance is handled by two tank TES by adjusting HTF level inside both tanks. However, the process that control CSP temperature can produce stable power for entire day while another approach cannot. Power production of process that control HTF flow rate is interrupted when sunrise.

For better understanding, level of HTF inside TES and its temperature is illustrated in Figure 30 and 31. As illustrated in Figure 33, level of HTF inside cold tank and hot tank of both process follow the same trend. During the day, CSP collects thermal energy from sunlight and transfer it by means of HTF. Hot tank utilizes HTF to fuel ORC to produce power while keep the excess HTF inside. Thus, level rises. During the night, CSP no longer collects thermal energy but HTF still flow from TES to transfer thermal energy for power production. This cause the level of HTF inside TES to drop.

Although the levels of HTF inside cold tank and hot tank behave similarly, HTF temperature inside hot tank does not. As illustrated in Figure 34, HTF temperature inside hot tank of the process that control HTF flow rate is lower than optimal temperature. When sunrise, HTF level inside hot tank hits its lowest level. Cold tank dispatches HTF to collect thermal energy from low solar irradiance results in low temperature HTF entering hot tank. HTF temperature is not enough to evaporate working from ORC efficiently. As a result, power production of the process drops. Thus, it can be concluded that process with two tank TES that control CSP temperature is more suitable for small-scale CSP than process that control HTF flow rate at CSP inlet.

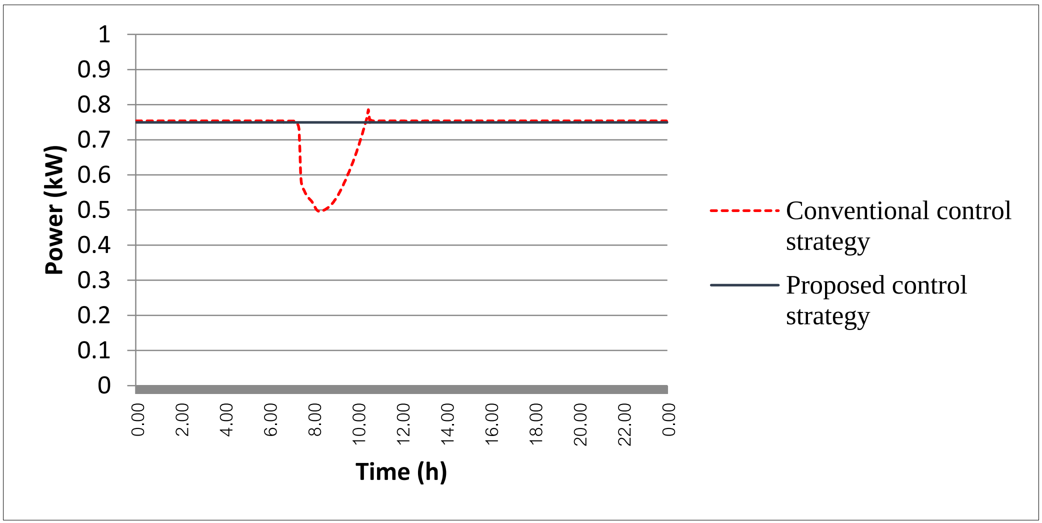

Figure 32. Power production of process with two tank TES using different controlled variables

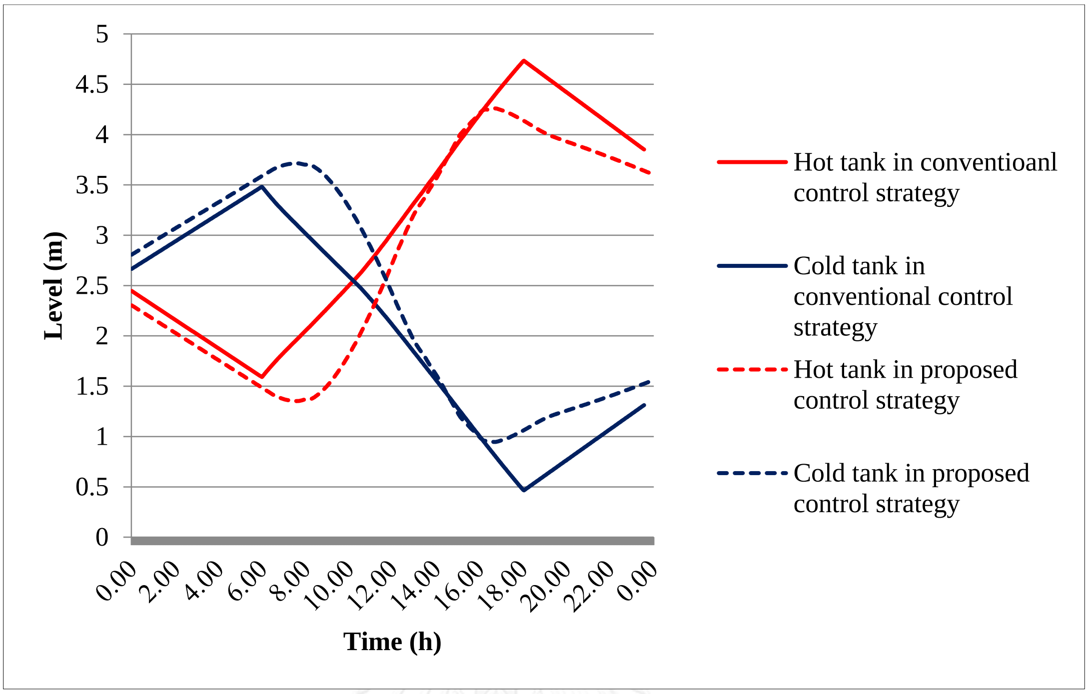

Figure 33. HTF level inside two tank TES

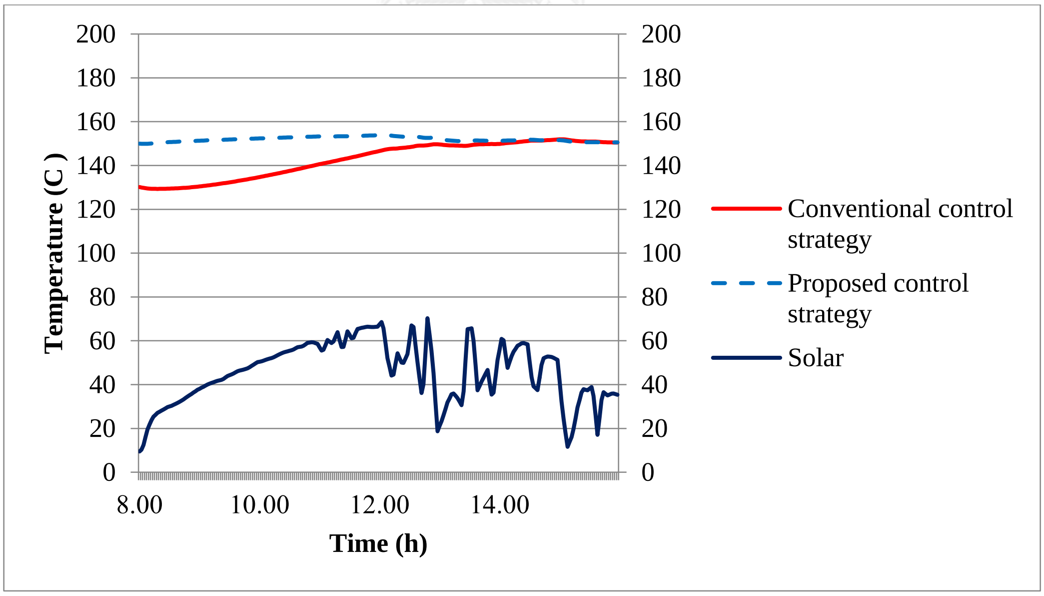

Figure 34. Temperature inside hot tank under disturbance from solar irradiance

In case of packed bed TES, Figure 35 shows power production of process with packed bed TES using different controlled variable. Both processes cannot produce power for entire day. The process that control HTF flow rate can produce power longer than another approach. However, the process that control HTF flow rate cannot produce stable power when sunset. To explain this problem, temperature of packed bed TES of both processes is illustrated in Figure 36 and 37.

As illustrated in Figure 36, temperature inside TES rises during the day because hot HTF flow from CSP flow through packed bed to store thermal energy. However, packed bed TES temperature at HTF inlet dramatically decrease when sunset because of low solar irradiance. The process shuts down automatically when temperature difference between working fluid inlet and packed bed TES temperature at HTF inlet is too low. As a results, there is no power production. Thermal energy inside packed bed TES cannot be harnessed to its fullest. Thus, the process needs to be manually controlled to start up power production.

In case of process with packed bed TES that use CSP temperature as controlled variable, the process can operate automatically because there is no rapid drop in temperature of packed bed TES at HTF inlet. The process start up faster than another approach due to HTF flow rate adjustment during low solar irradiance period. However, process that use HTF flow rate as controlled variable can still produce power longer than process that use CSP temperature as controlled variable. This problem will be discussed in the next section.

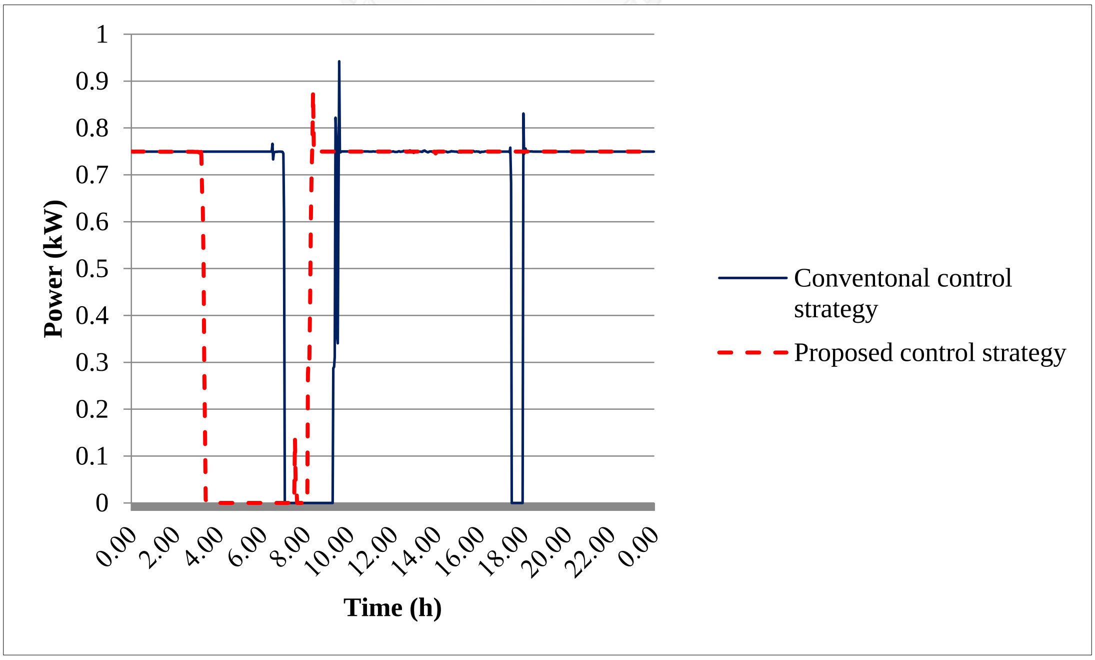

Figure 35. Power production of process with packed bed TES using different controlled variable

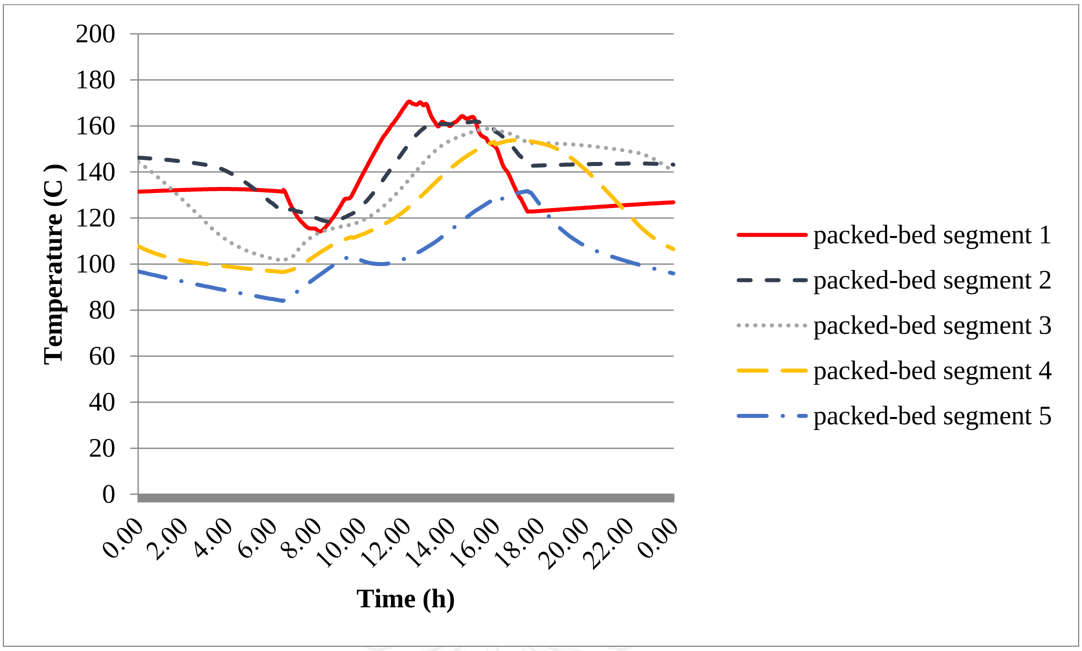

Figure 36. Temperature of packed bed TES that use conventional control strategy (segment 1 is the closest to HTF inlet and segment 5 is closest to HTF outlet)

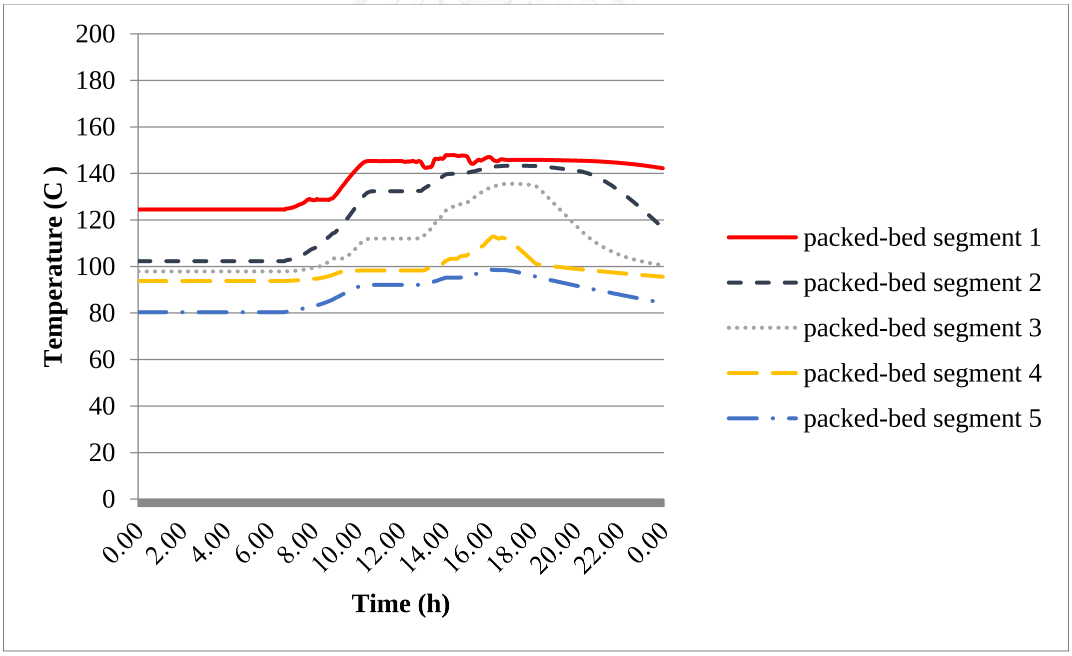

Figure 37. Temperature of packed bed that use control strategy 1 (segment 1 is closest to HTF inlet and segment 5 is closest to HTF outlet)

6.2.3 TES comparison

One of objective of this research is to study and compare dynamic behavior and performance of process with different TES. In this research, there are 2 kinds of TES: two tank TES and packed bed TES. Before both kind of TES is compared, the process should be controlled with suitable control strategy. There are 2 control strategies for process with packed bed TES. The dynamic behavior and power production of process with two tank TES and process with packed bed TES using control strategy 1 are discussed in previous section. Control strategy 2 is focus on control maximum temperature difference between packed bed inlet and outlet.

For process with packed bed TES using control strategy 2, Figure 38 shows 24-hour power production of process with packed bed TES that use control strategy 2. The process that use control strategy 2 can produce power for entire day while the process using control strategy 1 cannot. Control strategy 2 controls temperature difference between packed bed TES inlet and outlet which result in constant drive force for heat transfer between HTF and solid bed. Temperature of packed bed TES that use control strategy 2 is shown in Figure 39. Although temperature of packed bed TES in process that use control 2 follows the same trend as the process that use control strategy 1, control strategy 2 operate at higher temperature. As packed bed TES collect thermal energy, temperature of solid bed rises. CSP need to dispatch hotter HTF to maintain temperature difference at the set point until the temperature at expander inlet exceed its limitation and have to shut down CSP. The controller PID5 take control of the system instead of controller PID1. Valve V1 is closed to prevent hot HTF to enter packed bed TES while the process still produce power. Working fluid collects thermal energy from solid bed until the temperature at expander inlet drop below 175 °C. Then, controller PID1 is switched back to take control of the system and dispatch HTF to CSP. Unfortunately, it was switched on during night time. Cold HTF enter CSP with no thermal energy to receive and then enter high temperature packed bed TES. This result in temperature drop at packed bed TES inlet on HTF side.

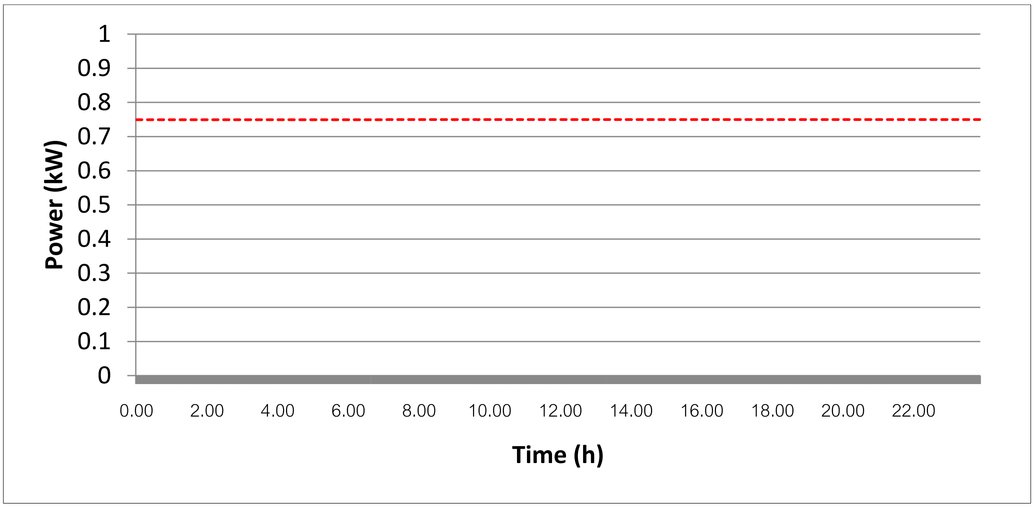

Figure 38. 24-hour power production of process with packed bed TES that use control strategy 2

For better understanding of the process, energy flow diagrams are made to show each systems energy and losses. Figure 40 and 41 illustrate energy flow of process with packed bed TES that use control strategy 1 and 2 in day 2. The total thermal energy from solar irradiance of both process are the same. However, energy loss in CSP is different because heat loss in CSP is depend on operating temperature. The process with packed bed TES that use control strategy 2 operates at higher temperature which result in more energy loss in CSP.

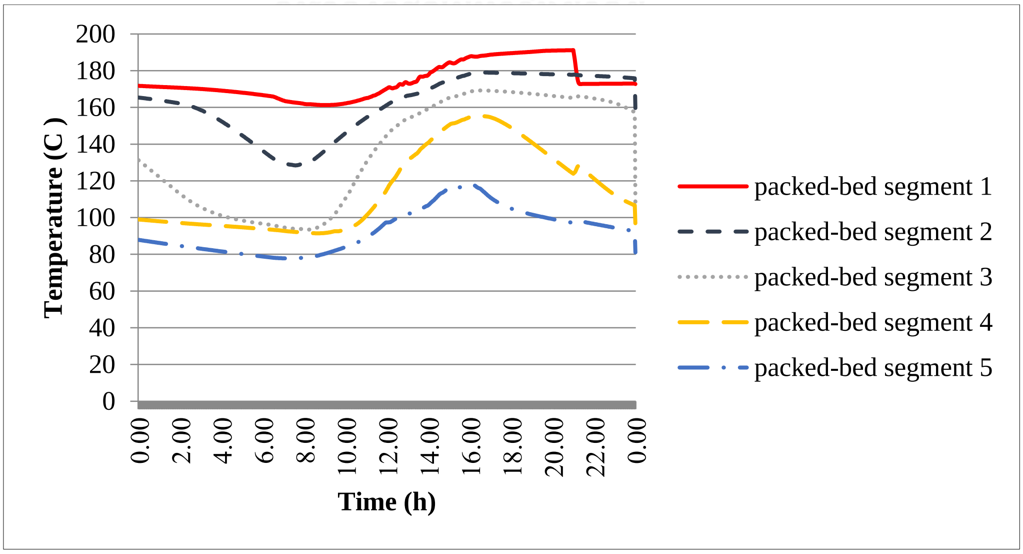

Figure 39. Temperature of packed bed that use control strategy 2 (segment 1 is closest to HTF inlet and segment 5 is closest to HTF outlet)

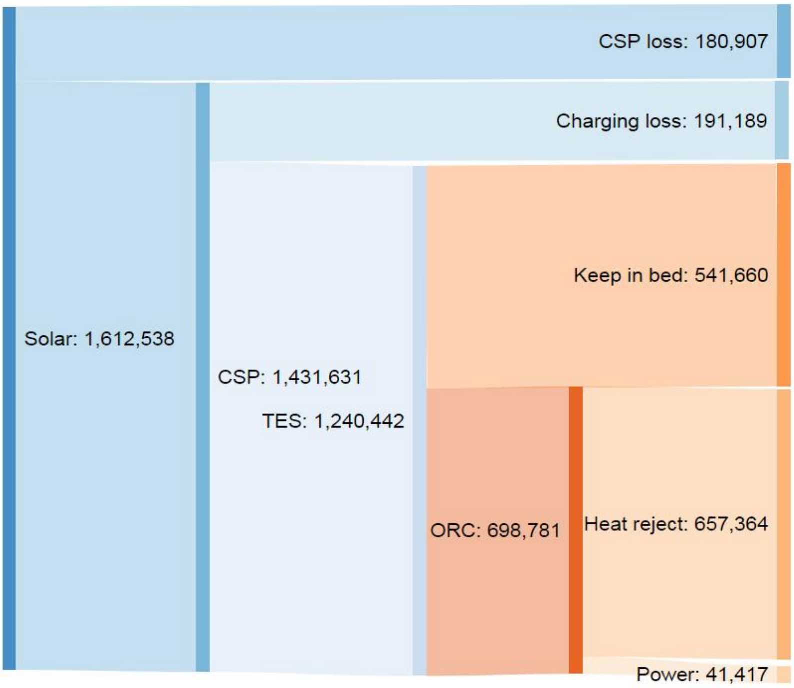

Figure 40. Energy flow diagram of process with packed bed TES using control strategy 1

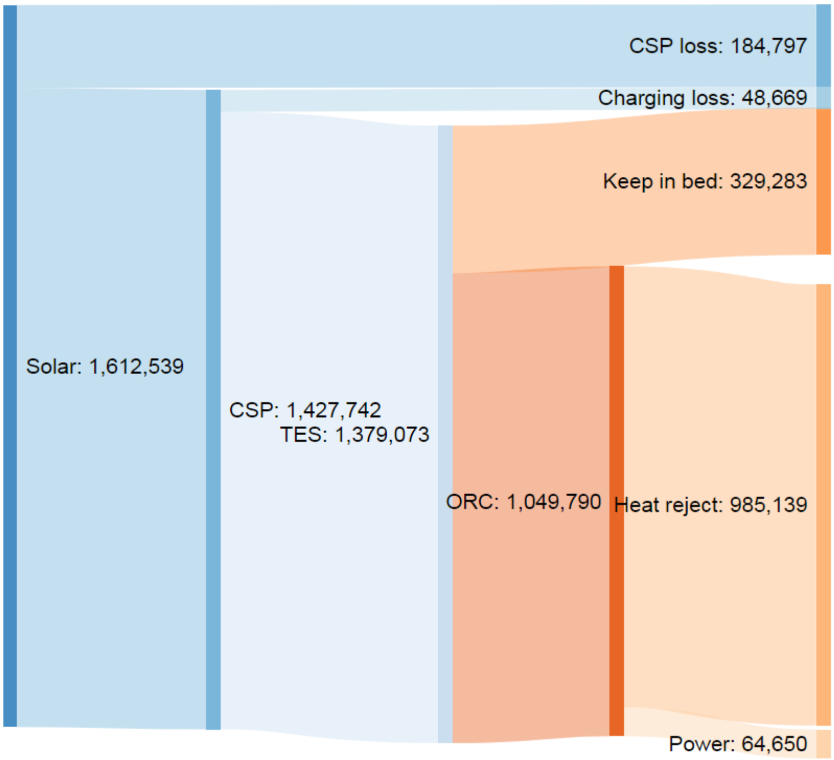

Figure 41. Energy flow diagram of process with packed bed TES using control strategy 2

Another energy loss in CSP is charging loss. Charging loss occurs when temperature of packed bed rises closed to temperature of HTF. The process with packed bed TES that use control strategy 1 has more charging loss than another process. When temperature of solid bed rises, the process that use control strategy 1 still supplied constant HTF temperature into packed bed TES causing temperature difference between HTF and solid to become less. Figure 42 shows comparison of temperature difference between packed bed TES inlet and outlet using different control strategy. Process with packed bed TES that use control strategy 2 adjusts HTF temperature from CSP to maintain the temperature difference at around 80°C while another approach still supplies HTF at constant temperature causing temperature difference to drop. The reduction of temperature difference between solid bed and HTF which is driving force for heat transfer results in more charging loss in process that use control strategy 1. This also explain why process with packed bed TES that use conventional control structure can produce more power than process that use control strategy 1. The temperature packed bed TES in process that use conventional control structure is vary according to solar irradiance.

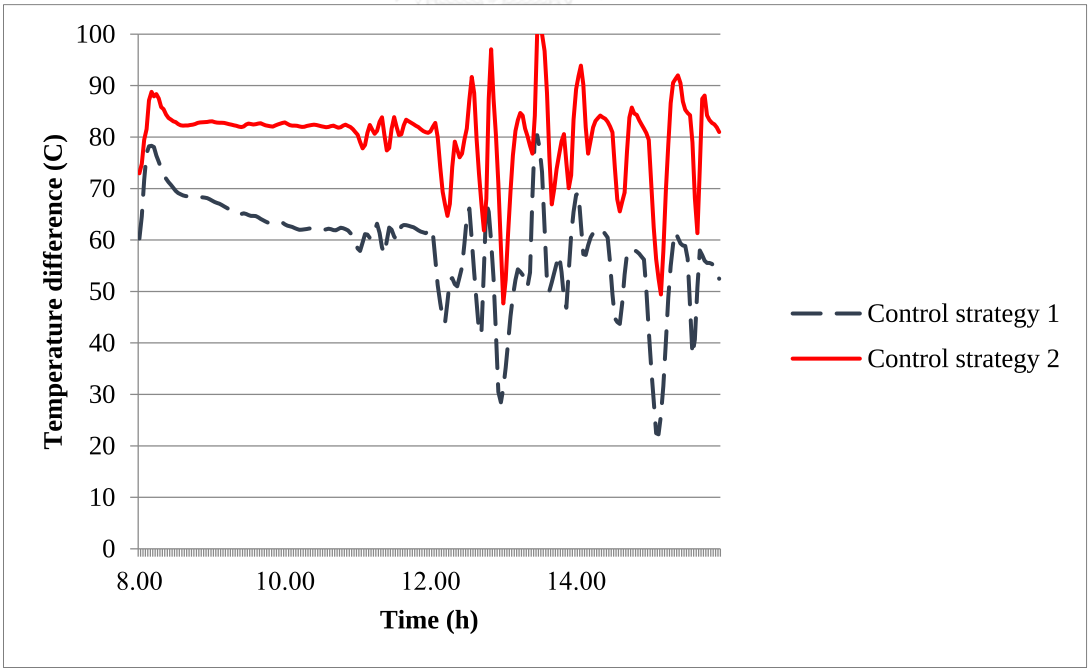

Figure 42. Temperature difference of process with packed bed TES using different control strategy

According to Figure 40 and 41, packed bed TES in process that use control strategy 2 can dispatch energy to ORC more than the process that use control strategy 1 because process that use control strategy 2 operates at higher temperature than another approach. As packed bed TES dispatches thermal energy to ORC, temperature of solid bed decrease until it unable to evaporate working fluid. Even though thermal energy is kept inside solid bed at the end of the day, it is unusable to generate power. Thus, process with packed bed TES that use control strategy 1 cannot produce power throughout whole day.

Figure 43 shows energy flow diagram for process with two tank TES in day 2. In case of two tank TES, TES stores the energy my means of hot HTF itself instead of solid sensible heat. This prevents charging loss to occur. The efficiency of two tank TES is 100% if heat loss through wall is neglected. Another advantage of using HTF itself as stored energy is that the energy that is kept inside TES at the end of the day is usable to produce power.

Overall efficiency of process which is explained by equation (13) is chosen as performance index. The overall efficiency of process with two tank TES, process with packed bed TES that use control strategy 1 and process with packed bed TES that use control strategy 2 are 5.4%, 2.6% and 4.0%, respectively. Therefore, process with two tank TES perform better than process with packed bed TES.

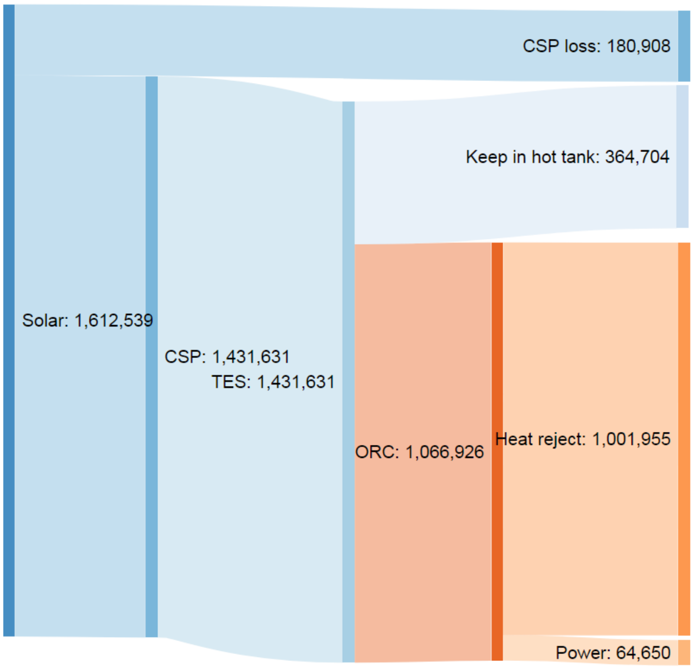

Figure 43. Energy flow diagram of process with two tank TES

Chapter 7
Conclusion and recommendation

7.1 Conclusion

This research focuses on study operability and control structure of small-scale CSP system integrated with ORC and two different types of TES, direct two tank TES and packed bed TES, for power production in individual household. Both processes are optimized and compared with each other. Steady-state and dynamic simulation are made to identify suitable TES for power production.

Steady-state simulation is used to determine the optimal operating condition of CSP and ORC by using overall efficiency as objective function. CSP is modeled after commercial parabolic trough technology using synthetic oil Dowtherm™A as HTF. A simple ORC with acetone as working fluid is selected to be power conversion system. The process require solar field area around 75 m^2. The highest overall efficiency obtained from steady-state simulation is 7.05%. Then, dynamic simulations are constructed to study overall process including CSP, TES and ORC. An actual solar irradiance data and model heat loss are added to CSP. Control structure of process in conventional solar power plant is discussed and designed for small-scale CSP using skogestad’s procedure. After considering control structure of process with packed bed TES, the packed bed TES is modified for easier operation. The storage is a combination of thermal energy storage and heat exchanger. Both control structure is studied and compared dynamic behavior. Proposed control strategy performs better than conventional control strategy in handling disturbance from solar irradiance and automatic power production. In term of TES comparison, both TES are able to produce stable power despite of solar availability. Two tank TES is 31.14 m^3 in total while packed bed TES is only 22 m^3. Hence, packed bed TES is significantly smaller than two tank TES. In term of process performance comparison, packed bed tank can yield only 4.0% of overall efficiency of the process while two tank TES yield 5.4% when heat loss is neglected.

7.2 Recommendation

In future work, an economic analysis should be taken into account for comparison of these thermal energy storage.

REFERENCES

Abutayeh, M., et al. (2015). "Optimizing thermal energy storage operation." Solar Energy **120**: 318-329.

Angelini, G., et al. (2014). "Comparison of Thermocline Molten Salt Storage Performances to Commercial Two-tank Configuration." Energy Procedia **49**: 694-704.

Cascetta, M., et al. (2014). "Numerical Investigation of a Packed Bed Thermal Energy Storage System with Different Heat Transfer Fluids." Energy Procedia **45**: 598-607.

Dickes, R., et al. (2015). Semi-empirical correlation to model heat losses along solar parabolic trough collectors. 28th ECOS conference.

Ferrara, F., et al. (2014). "Small-scale Concentrated Solar Power (CSP) Plant: ORCs Comparison for Different Organic Fluids." Energy Procedia **45**: 217-226.

Gil, A., et al. (2010). "State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization." Renewable and Sustainable Energy Reviews **14**(1): 31-55.

Ireland, M. K. (2014). Dynamic modeling and control strategies for a micro-CSP plant with thermal storage powered by the Organic Rankine cycle, Massachusetts Institute of Technology.

Manenti, F. and Z. Ravaghi-Ardebili (2013). "Dynamic simulation of concentrating solar power plant and two-tanks direct thermal energy storage." Energy **55**: 89-97.

Moore, R. L. (2010). "Implement of DOWTHERM A Properties into RELAP5 - 3D/ATHENA."

Ravaghi-Ardebilli, Z., et al. (2013). "Study of direct thermal energy storage technologies for effectiveness of concentrating solar power plants." The Italian Association of Chemical Engineering (AIDIC) **32**.

Skogestad, S. (2004). "Control structure design for complete chemical plants." Computers & Chemical Engineering **28**(1–2): 219-234.

Vitte, P., et al. (2012). "Dynamic simulation of concentrating solar plants." Chemical Engineering Transactions **29**: 235-240.

Zanganeh, G., et al. (2012). "Packed-bed thermal storage for concentrated solar power – Pilot-scale demonstration and industrial-scale design." Solar Energy **86**(10): 3084-3098.

APPENDIX

VITA

Mr. Sittiporn Vongsilodkul was born on February 11, 1992 in Nonthaburi province, Thailand. In 2010, he finished high school from Suankularb Wittayalai Nonthaburi, in 2014, he graduate the Bachelor’s Degree in Chemical engineering from King Mongkut's University of Technology Thonburi. He continued studying the Master’s Degree of engineering in Chemical Engineering at Chulalongkorn University and joined Computational Process Engineering Research Center.